PB89-155063

Prevention Reference Manual
Control Technologies. Volume 2
Post-Release Mitigation Measures for Controlling Accidental Releases of Air Toxics

Radian Corp., Austin, TX

Prepared for

Environmental Protection Agency
Research Triangle Park, NC

Jan 89

U.S. Department of Commerce
National Technical Information Service
NTIS

PB89-155063

EPA/600/8-87/039b
January 1989

PREVENTION REFERENCE MANUAL: CONTROL TECHNOLOGIES

VOLUME 2: POST-RELEASE MITIGATION MEASURES FOR CONTROLLING ACCIDENTAL RELEASES OF AIR TOXICS

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Contract No. 68-02-3994
Work Assignment 102
and
Contract No. 68-02-4286
Work Assignment 41

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NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA/600/8-87/039b	2.	3. RECIPIENT'S ACCESSION NO. PB89 155063/AS
4. TITLE AND SUBTITLE Prevention Reference Manual: Control Technologies, Volume 2: Post-release Mitigation Measures for Controlling Accidental Releases of Air Toxics		5. REPORT DATE January 1989
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) D. S. Davis, G. B. DeWolf, K. A. Ferland, D. L. Harper, R. C. Keeney, and J. D. Quass		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Radian Corporation Austin, Texas 78720-1088		10. PROGRAM ELEMENT NO.
		11. CONTRACT/GRANT NO. 68-02-3994, Task 102, and 68-02-4286, Task 41
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Air and Energy Engineering Research Laboratory Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Task Final; 6/87 - 9/88
		14. SPONSORING AGENCY CODE EPA/600/13

15. SUPPLEMENTARY NOTES AEERL project officer is T. Kelly Janes, Mail Drop 62B, 919/541-2852.

16. ABSTRACT

The report covers post-release mitigation measures to control accidental releases of air toxics. Reducing the possibility of accidental toxic chemical releases reduces the possibility of harm to human health and to the environment. When such a release does occur, however, its consequences must be reduced. This can be accomplished by a variety of mitigation measures that can contain, capture, destroy, divert, or disperse the released chemical. Mitigation measures begin with the initial siting and layout of a facility to decrease the area that would be affected by a release. The extent of the area potentially affected, the concentrations of toxic chemicals reaching those areas, and the duration of exposure can be estimated by vapor or gas dispersion modeling. The extent and magnitude of an actual release can be determined using meteorological instruments. These systems, along with emergency planning and training, are the first steps in the mitigation process. Other measures involve the use of mitigation techniques such as leak plugging, containment systems, and spray or foam systems. The general application costs of these methods are discussed.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Maintenance	Pollution Control	13B	15E
Chemical Plants	Education	Stationary Sources	07A	15I
Emission	Management	Air Toxics	14G	15A
Toxicity		Chemical Releases	06T	
Chemical Compounds		Training	07B, 07C	
Accidents			13L	
Design				

18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 214
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

NOTICE

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ABSTRACT

Reducing the probability of accidental toxic chemical releases reduces the possibility of harm to human health and to the environment. When such a release does occur, however, its consequences must be reduced. This can be accomplished by means of a variety of "mitigation" measures that contain, capture, destroy, divert, or disperse the released toxic chemical.

Mitigation measures begin with the initial siting and layout of a facility to decrease the area that would be affected by a release. The extent of the areas potentially affected, concentrations of toxic chemicals reaching those areas, and the duration of exposure can be estimated by vapor or gas dispersion modeling. Detection and warning systems give the first notice of a release, and the actual extent and magnitude can be determined by meteorological instruments. These systems, along with emergency planning and training, are the first steps in the total mitigation process. Other measures involve the use of specific mitigation techniques, such as leak plugging, containment systems, and spray or foam systems.

Mitigation measures are described and discussed in terms of their applicability, performance, state of development, and general application costs. This manual is part of a multi-volume series of manuals that address the prevention of accidental releases of toxic chemicals.

ACKNOWLEDGEMENTS

This manual was prepared under the overall guidance and direction of T. Kelly Janes, Project Officer, with the active participation of Robert P. Hangebrauck, William J. Rhodes, and Jane M. Bare, all of U.S. EPA. In addition, other EPA personnel served as reviewers. Radian Corporation principal contributors were Graham E. Harris (Program Manager), Glenn B. DeWolf (Project Director), Daniel S. Davis, D. L. Harper, R. C. Keeney, Jeffrey D. Quass, and Sharon L. Wevill. Contributions were also made by other staff members. Secretarial support was provided by Roberta J. Brouwer and Bonita Cross. Special thanks are due many other people, both in government and industry, who served in the Technical Advisory Group and as peer reviewers.

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SECTION 1

INTRODUCTION

Increasing concern about the potentially disastrous consequences of major accidental releases of toxic chemicals resulted from the Bhopal, India, methyl isocyanate release on December 3, 1984, which killed approximately 2,000 people and injured thousands more. Concern about the safety of process facilities that handle hazardous materials increased further after the accident at the Chernobyl nuclear power plant in the Soviet Union in April of 1986.

While headlines of these incidents have created the current awareness of toxic release problems, other, perhaps less dramatic, incidents have occurred in the past. These accidents contributed to the development of the field of loss prevention as a recognized specialty area within the general realm of engineering science. Interest in reducing the probability and consequences of accidental toxic chemical releases that might harm workers within a process facility and people in the surrounding community prompted preparation of this manual and a series of companion manuals.

This manual, which addresses the post-release mitigation measures for toxic chemical releases, is designed to give the reader useful information about the state of the art in this area. Post-release mitigation measures are defined as any measures that may reduce the consequences of an accidental toxic chemical release after it has occurred. Mitigation measures decrease the quantity of a released chemical that can reach receptors, decrease the area exposed to the chemical, and/or reduce the duration of exposure. The emphasis is on post-release mitigation measures for facilities that handle toxic chemicals so that the potential risk to surrounding communities can be minimized.

Companion volumes to this manual include:

Prevention Reference Manual: User's Guide Overview for Controlling Accidental Releases of Air Toxics (1)
Prevention Reference Manual: Chemical Specific, Volume 8: Control of Accidental Releases of Hydrogen Fluoride (3)
Prevention Reference Manual: Control Technologies, Volume 1: Prevention and Protection Measures for Controlling Accidental Releases of Air Toxics (2)

The series also contains several chemical-specific manuals on controlling accidental releases of specific chemicals. An example is the Prevention Reference Manual: Chemical Specific, Volume 8: Control of Accidental Releases of Hydrogen Fluoride (3).

1.1 FUNDAMENTAL CONCEPTS

The physical release of a chemical is the final event in a sequence of events leading to the release. Such a sequence of events begins with the initiating, or primary, event and propagates through enabling events. The final event can be prevented by preventing the initiating event or the enabling events. Success in preventing a release depends on correctly identifying primary and enabling events and event chains, on knowing the relative probability of the events, and on the skill and knowledge of the individuals charged with conducting the analysis. If prevention and protection meausures fail and a release occurs, mitigation measures must be invoked.

Figure 1-1 illustrates the place of mitigation, among other measures, in reducing the ultimate consequences of a potential release. As seen in the figure, mitigation can be viewed as one of several barriers between a release hazard and realization of its consequences. Before appropriate mitigation

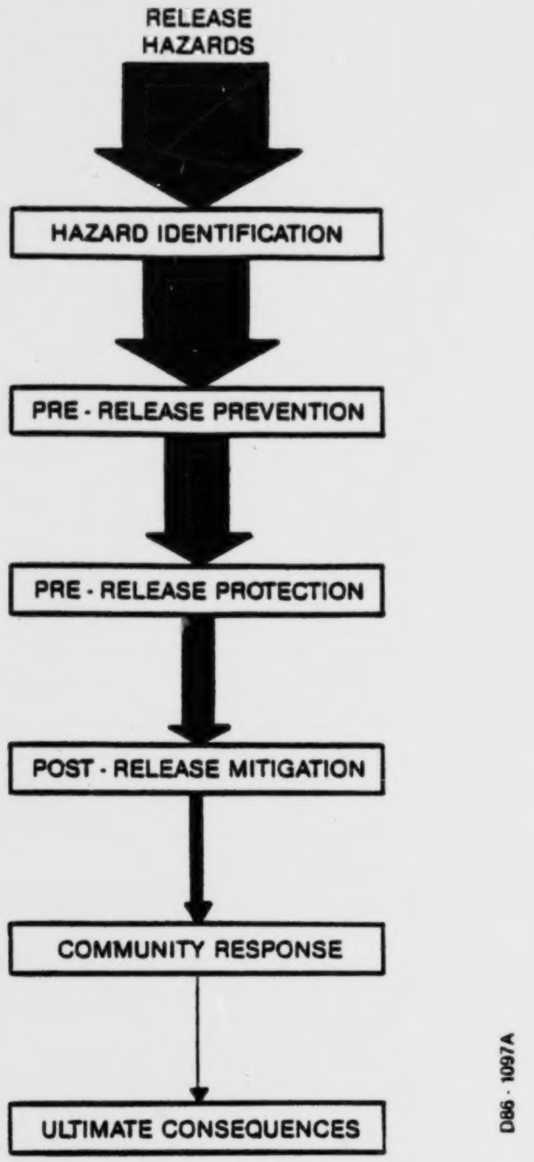
RELEASE HAZARDS
HAZARD IDENTIFICATION
PRE - RELEASE PREVENTION
PRE - RELEASE PROTECTION
POST - RELEASE MITIGATION
COMMUNITY RESPONSE
ULTIMATE CONSEQUENCES
D86 - 1097A

Figure 1-1. The role of various accidental release control measures in reducing the consequences of an accidental release.

measures can be determined, the potential consequences of a release must be determined. The mitigation measures addressed in this manual include: 1) emergency planning; 2) siting and layout; 3) dispersion modeling; 4) detection and warning systems; 5) meteorological instrumentation; and 6) technical mitigation measures that can effectively control a release.

Emergency planning and training ensure the rapid and correct response of the people charged with applying other mitigation measures and define what mitigation measures should be employed.

Plant siting and layout concerns the placement of hazardous facilities relative to sensitive receptors in the surrounding community and within plant boundaries. Important considerations in this area, besides the obvious distance factor, include taking advantage of terrain features such as hills that might act as natural barriers, and avoiding the funneling effects of valleys.

Detection and warning systems give advance notice that a release is incipient or has occurred and define the magnitude and location of the release so that other mitigation measures can be taken. Meteorological instrumentation serves a similar purpose by providing data needed to monitor the physical location and movement of a release and the ambient characteristics that affect the movement and dispersion of a vapor or gas plume or cloud.

Vapor dispersion modeling is used to predict the extent, duration, and concentration of the plume or cloud of released toxic vapor or gas. Numerous dispersion models of varying levels of sophistication, accuracy, and verification by actual field data are available. The results predicted by these models depend on a source term which describes the characteristics of the initial release, and a dispersion term that describes the characteristics of the resultant cloud or plume. Characteristics of the release are primarily process and process equipment related, while dispersion characteristics are related to the properties of the chemical vapor or gas and to meteorological conditions. Such models can inform decisions about plant siting and layout, the placement of detection and warning systems and meteorological instrumentation, and the selection of technical mitigation measures.

Containment systems reduce the area that could be exposed to vapors from a release and confine the liquid portion of a release until measures can be taken to recontain or destroy the released chemical. While some containment may be successful with gases, containment is probably more applicable to spilled volatile liquids.

Spray systems disperse, dilute, and absorb a released airborne chemical. Spray systems rely on fixed or mobile equipment that applies a spray of water, other materials, or a condensing cloud of steam directly to the cloud or plume of noxious chemical. Some spray systems for toxic gas releases are similar to fire fighting systems.

Foam systems are primarily used to contain volatile liquid evaporation from pools of spilled liquid. These systems are based on specialty chemical materials that generate foams whose specific characteristics are tailored to the chemical properties of the material to which they are applied. Foams act as a physical barrier to prevent or decrease evaporation from liquid surfaces.

1.2 ORGANIZATION OF THE MANUAL

The remainder of this manual is divided into 8 sections, beginning with Section 2. Sections 2 through 6 deal with mitigation measures that enable a plant to prepare for an accidental release and to respond appropriately if one occurs. Sections 7 through 9 discuss the technologies used to control the liquid and vapor potions of an accidental release.

Section 2 addresses emergency planning and training, which are essential components of the mitigation effort. In Section 3, facility siting and layout as related to mitigation are discussed. Detection and warning systems within the facility and outside the facility boundary are discussed in Section 4.

Section 5 covers the basic types of vapor dispersion models and discusses the applicability of these models to the mitigation problem. Meteorological instrumentation, as described in Section 6, allows real-time estimates of where, when, and to what extent a release will affect the community.

Section 7 introduces the topic of secondary containment measures, or those measures that can control the spread of a toxic release once it occurs. The last three sections of the manual discuss three technologies that may be used to reduce hazardous vapor concentrations, thereby minimizing their effect on surrounding communities. These technologies are spray and steam systems, covered in Section 8, and foam systems, covered in Section 9.

Appendices contain tables for converting between English units of measure (used throughout the manual) and SI metric units. A glossary of terms also appears in the appendix.

1.3 REFERENCES

1. Davis, D.S., G.B. DeWolf, and J.D. Quass. Prevention Reference Manual: User's Guide Overview for Controlling Accidental Releases of Air Toxics. EPA-600/8-87-028 (NTIS PB87-232112), U.S. Environmental Protection Agency, AEERL, Research Triangle Park, North Carolina, 1987.

2. Davis, D.S., G.B. DeWolf, and J.D. Quass. Prevention Reference Manual: Control Technologies, Volume 1. Prevention and Protection Technologies for Controlling Accidental Releases of Air Toxics. EPA-600/8-87-039a (NTIS PB87-229656), U.S. Environmental Protection Agency, AEERL, Research Triangle Park, North Carolina, 1987.

3. Davis, D.S., G.B. DeWolf, and J.D. Quass. Prevention Reference Manual: Chemical Specific, Volume 8. Control of Accidental Releases of Hydrogen Fluoride. EPA-600/8-87-034h (NTIS PB87-234530), U.S. Environmental Protection Agency, AEERL, Research Triangle Park, North Carolina, 1987.

SECTION 2

EMERGENCY PLANNING AND TRAINING

Emergency planning and training are an integral part of mitigation. Reducing the consequences of an accidental release depends on a timely, effective response by people at the scene who know the what, when, where, and how of various countermeasures. This includes the application of various technical mitigation measures discussed elsewhere in this manual, as well as calling for assistance, notifying authorities, and, if necessary, evacuating people from the affected areas.

2.1 BACKGROUND

Numerous recent publications on emergency preparedness include sections on emergency planning and training. The U.S. EPA has published a guidance manual on the Chemical Emergency Preparedness Program (1). The Chemical Manufacturer's Association has sponsored the Community Awareness and Emergency Response (CAER) program (2,3). Other publications also deal with the issue (e.g., Reference 4).

2.2 EMERGENCY PLANNING

2.2.1 Description

The details of emergency planning and training will vary from facility to facility and community to community. In general, however, any program should address certain fundamental elements:

- Program initiation;

- Hazard evaluation;
- The identification, evaluation, selection, and implementation of countermeasures;
- Resource requirements and availability;
- Organization; and
- Mobilization and demobilization.

Emergency programs may be initiated by facility or corporate personnel or by an outside authority. Once the program is started, an overall plan can be developed to address each of the other fundamental elements listed above. The plan should address community involvement as well as on-site emergency planning and response activities. This is discussed further in Subsection 2.2.2.

Evaluating the potential hazards of a particular facility, which involves both hazard identification and analysis, is an essential starting point in actual plan development. Hazard identification begins with a list of designated chemicals, a determination of which ones are present at the facility, the quantities, and their physical states. The identification of potential release hazards is based on physical and toxicological data and on how the chemicals are used at the facility. The potential hazards are then analyzed to determine how release incidents might occur and what the consequences might be. These topics are examined more fully in other manuals in the Prevention Reference Manual series, as well as in the technical literature. Various formal procedures can be followed to more effectively determine the relative probability and consequences of various release scenarios.

Once the potential accidental release scenarios are known, countermeasures can be proposed for incorporation into the emergency plan. Since there may be more than one acceptable response to a given emergency situation, the various response measures must be evaluated to select those that appear most effective for the specific scenarios under consideration. The final step is to implement the measure(s) when an emergency occurs.

Two other important subjects to consider when designing an emergency plan are resource requirements and availability, and emergency organization. Resource requirements include personnel, equipment, and money to fund both the plan and its implementation. Personnel requirements and equipment needs should be explicitly noted, while funds should be allocated in management budgets but not explicitly addressed in the plan. An on-going financial commitment will be required for periodic reviews and updates of the plan, as well as for training programs. Availability addresses what resource additions may be required that are not already present in a facility, company, or community. The emergency organization must be clearly defined. The function of the emergency organization is to establish clear lines of communication and define responsibilities and authority so that confusion, delays, and inappropriate actions can be avoided during an emergency.

Finally, a complete plan must address mobilization--how the plan will be activated in an emergency--and demobilization--how the plan will be concluded after an emergency.

The plan should be documented; the emergency response plan (ERP) documents the planning activities and provides a ready reference for use during emergencies. The ERP must be a "living document," that is, frequently updated to reflect changes in equipment, staff, and the facility. The ERP should include the following major topics:

- General facility description, including plot plans and area maps;

- Description of hazards associated with facility operations (detailed assessments should be included or attached);
- Description of the organization of personnel involved in emergency response;
- Functions, responsibility, and authority of key personnel;
- Location and equipment of each emergency control center;
- Alarm systems and notification;
- Description of all communication systems and emergency backups;
- Ranked list of notifications that must be made for each type of accident;
- Evacuation and/or sheltering plans for non-essential personnel;
- Assembly points and procedures for accounting for all employees, visitors, contractors, and others;
- Locations of and equipment stored at each on-site first aid center;
- Transportation facilities and likely locations of vehicles; including specialty vehicles like trackmobiles, cranes, front-end loaders, and others;
- Security precautions;
- Continuation of utilities and services;
- Local emergency response agencies;

- Mutual aid organizations;
- Possibility of and procedures for community evacuation;
- Community shelter-in-place potential;
- Community emergency education;
- Public relations in an emergency;
- Procedures and equipment for responding to
  - fires and/or explosions,
  - toxic materials releases,
  - floods,
  - hurricanes (if applicable to location),
  - ice storms,
  - other natural phenomena (earthquakes, tornados, etc.),
  - civil disturbances;
- Restoration of normal operations;
- Training in emergency response procedures;
- Drilling in emergency response procedures;
- Emergency systems training and maintenance; and
- Emergency response plan updates.

The appropriate depth of planning for each of these topics depends on the nature/severity of the potential hazard, the size and complexity of the plan, and the use of the facility relative to the use of outside agencies for fire fighting, first aid, etc.

One sample outline of a community emergency response plan published by the U.S. EPA is shown in Table 2-1 (1). The details of this approach are discussed in the reference. Comparison of this approach with the previous discussion illustrates that, while certain topics are common to both industrial and community plans, individual details may be addressed in different ways.

2.2.2 Implementation

Implementation of an emergency response plan, including coordination between the facility and the community, has been addressed by both the U.S. EPA and the chemical industry (1,2,3).

One formal, collective chemical industry initiative is the Community Awareness and Emergency Response program developed under the auspices of the Chemical Manufacturers Association (3). Its purpose is to prepare communities to respond effectively to man-made or natural disasters. The goals of the program are to improve community awareness and to integrate industrial emergency response plans with those of the community. Some objectives of CAER are to:

- Inform the public about hazardous chemicals;
- Review, renew, or establish emergency response plans;
- Integrate chemical facility emergency response plans with those of the community to form an overall plan for handling all emergencies; and
- Involve members of the local community in developing and implementing overall emergency response planning.

TABLE 2-1. EXAMPLE OUTLINE OF A COMMUNITY EMERGENCY RESPONSE PLAN

- i. Emergency Response Notification Summary
- ii. Record of Amendments
- iii. Letter of Promulgation
- iv. Acknowledgment
- v. Table of Contents

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- A. Abbreviations and Definitions
- B. Purpose
- C. Relationship to Other Plans
- D. Assumptions/Planning Factors
- E. Concept of Operations
  - 1. Governing Principles
  - 2. Organizational Roles

II. Emergency Response Operations

- A. Notification of Release
- B. Initiation of Action
- C. Coordination of Decision-Making
- D. Public Information/Community Relations
- E. Personal Protection/Evacuation
- F. Resource Management
- G. Personnel Safety
- H. Acutely Toxic Chemicals
- I. Countermeasures
- J. Response Action Checklist
- K. Attachments
  - 1. Emergency Assistance Telephone Roster
  - 2. Siren Coverage
  - 3. Emergency Broadcasting System Messages
  - 4. Evacuation Routes
  - 5. Traffic Control Points
  - 6. Access Control Points
  - 7. Evacuation Routes for Special Populations

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  - 1. Legal Authority and Responsibility for Responding
  - 2. Acutely Toxic Chemicals Information
  - 3. Hazards Identification and Analysis
  - 4. Response Organization Structure/Coordination
  - 5. Laboratory, Consultant, and Other Technical Support Resources
  - 6. Computer Utilization
- B. Post-Emergency Operations
  - 1. Documentation of Accidental Releases
  - 2. Investigative Follow-Up

A CAER Handbook has been prepared that gives detailed information on organizing and implementing a CAER Program (3). Major steps in a CAER program are:

- Community status review and program organization;
- Facility status review;
- Implementation;
- Community involvement; and
- Emergency exercises.

Community Status Review--

This review involves a survey of the status of local emergency planning in communities within a few miles around a facility. It seeks to determine whether integrated community emergency response planning is a complex activity (multifacility/hazard) or a local chemical facility function. Factors that should be considered are:

- Are there significant natural disaster risks in the area and do emergency plans exist for these risks?
- Are there other hazardous industrial activities, such as nuclear power generation, hazardous waste disposal, or significant transportation activities, and do emergency plans exist for these hazards?
- Are there other chemical facilities in the area?

- Does the facility's own emergency response plan clearly define the roles and responsibilities of community officials and off-site responders?

Based on this information, a status report can be prepared that describes the facility, the key elements of the facility emergency response capability, the objectives of CAER, and other pertinent issues. It should stress the need for off-site emergency response planning to be integrated with the existing facility emergency response capability, and that an integrated facility-community plan can be used to improve emergency response to all hazards.

- As a facility initiative in getting the CAER program underway, this document can be distributed and discussed with selected community contacts. The CAER program is explained to other people who should be involved in community emergency response planning as they are identified. These people will probably include first responders such as the fire chief, police chief, ambulance service workers, mutual aid program participants, local officials, business leaders, and facility employees, who may also be elected officials. Local disaster preparedness officials may be helpful as initial contacts.

- These initial contacts will identify the appointed and elected officials whose cooperation will be necessary to complete the integrated community emergency planning process. Meetings with key officials should be used to enlist their support in establishing a coordinating group. In many locations, the equivalent of this group or of a well-defined emergency response planning agency may already be in place.

A more formal preliminary organizational meeting for the coordinating group is a next step. Participants should include members of the groups listed above. Other participants could be public health officials, hospital administrators, Red Cross personnel, or local civic leaders. In most areas, chief elected officials have a general charter to protect public safety. Gaining official recognition from the local community is an important prerequisite for the coordinating group. This gives the group the necessary authority to begin the integrated planning process described later in this discussion.

Facility Status Review--

A number of activities are required. A first step is to review the facility emergency response plan to ensure that interactions with off-site agencies and responders are clearly defined. Responsibilities and notification procedures should be clearly defined.

- Employee awareness of emergency response planning must be provided for by ensuring that basic emergency concepts are included in initial training and periodic safety training. The facility newsletter or bulletin boards can announce that the facility has completed a new or revised company plan and has started an integrated emergency response planning process.

- A written community relations plan should be prepared. This can begin with a list of local organizations, government agencies, community groups (business, civic, public interest) and local media who should be briefed on the CAER program. Past local media coverage of the facility and national industry issues should be reviewed. Past and ongoing facility communications efforts should also be reviewed and it should be determined whether the community and its leaders are likely to be knowledgeable about the facility. Using this information, assign priority to community awareness efforts. Pay special attention to relations with local officials, off-site responder groups, neighborhood associations and labor groups. It may be appropriate to obtain expert assistance in community relations if this is a new activity for the facility.

Assured that the internal emergency planning activities are in order and that the appropriate coordinating group has been established, the facility's first contribution should be a presentation of a ten-step implementation process to the coordinating group.

Implementation Steps--

Ten implementation steps are defined under the CAER program:

- Identify the emergency response participants and establish their roles, resources and concerns;
- Evaluate the risks and hazards that may lead to emergency situations in the community;
- Have participants review their own emergency plan for adequacy relative to a coordinated response;
- Identify the required response tasks not covered by existing plans;
- Match these tasks to the resources available from the identified participants;
- Make the changes necessary to improve existing plans, integrate them into an overall community plan and achieve agreement;
- Commit the integrated community plan to writing and obtain approvals from local governments;
- Educate participating groups about the integrated plan and ensure that all emergency responders are trained;
- Establish procedures for periodic testing, review, and updating of the plan; and

- Educate the general community about the integrated plan.

2.3 TRAINING

The emergency response plan, which reflects the character of a specific facility, determines the basic training needs, which will vary with different groups within the facility according to their designated roles in an emergency. The general objectives of training are to increase the awareness, knowledge, and skills of management, and of operating, maintenance, and specialized emergency response personnel. Emergency exercise activities, suggested by CAER, involve integrated training with community emergency personnel.

2.3.1 Training Overview

As defined by one author, training must address employee roles in three stages of an emergency (4):

- Raising the alarm;
- Declaring that an emergency exists; and
- Implementing the emergency plan.

The training must ensure that personnel understand their roles in the general areas of:

- Communications and control procedures;
- Individual responsibilities;
- Specific emergency operating and countermeasure procedures;

- Coordination with outside services; and

- Public relations.

There are two distinct functional aspects of training: procedures and equipment. Procedures include the safe shutdown of a facility, communications, first aid and medical response, evacuation, traffic control, rescue, fire fighting, and the implementation of other counter measures.

Equipment-oriented training deals with both protective and remedial equipment, including: protective clothing and breathing apparatus, facility shutdown and control, fire fighting, leak control, spill control, meteorological monitoring, movement of equipment, emergency construction, and actuation of hardware safety systems.

To be effective, a training program must be ongoing, periodically reviewed, updated and revised, and have full management support to ensure that the necessary training resources are available. Management provides the environment for adequate training development and presentation through guidelines and policies and also the enforcement and incentives to make the program work. The initial training of personnel should give a thorough grounding in fundamentals and be followed by subsequent enhanced training in critical emergency areas. The development of an effective training program depends on a thorough task analysis of the various personnel roles defined in the emergency response plan.

The conduct of training should include on-the-job training, seminar/discussion sessions, formal classroom training, and field exercises. The support that vendors of equipment and technical services can provide should not e overlooked. Such outside influences can inspire new interest in otherwise routine in-house programs. Full advantage should also be taken of newer training tools such as video tapes and computer simulation.

In-depth training should be given to employees soon after they are hired and should include a review of facility hazards, general emergency response activities, the emergency response plan, and the specific duties of the new employee. This level of training should be repeated each time an employee moves to a new position in the facility with different hazards and different emergency response duties.

Refresher training should be given regularly. The frequency of refresher training should be based on the nature of the hazards and on the type of emergency response duties assigned to the employee.

Drilling is an important part of training. While the objective of training is to teach employees the appropriate response, the objective of drilling is to improve response time. Drills should be held for each type of hazard present at the facility. A combination of announced and surprise drills should be used. Outside agencies should be included in some drills. The employees should be given feedback on drill performance and supplemental training when performance is seriously deficient.

Decisions about the frequency of drills should be based on the nature/severity of the hazards, the size/complexity of the facility, and the amount of reliance on outside emergency aid.

Drills are discussed further as part of emergency exercise programs in Subsection 2.3.3.

2.3.2 Training Coordination with Outside Agencies

Fire departments, police, emergency medical services, mutual aid groups, and commercial emergency response contractors can help substantially during a facility emergency. The effectiveness of these outside agencies depends, however, on their knowledge of the facility, the processes, and the chemicals involved. Representatives of these agencies should regularly tour the facility and be trained in its hazard-related features. A spirit of open communications and cooperation should be fostered.

2.3.3 Emergency Exercise Program

An emergency exercise program is an essential part of CAER. It completes the cycle begun when the facility, along with community and industry representatives, formed a community coordinating group to manage emergencies. The coordinating group integrated all emergency plans into one community emergency response plan. Emergency responders have their tasks, and resources are committed. An emergency response system is in place, but will it work?

Besides a real emergency, only the simulation of an emergency can answer that question. Simulation and evaluation exercises, by testing all or part of a system against the plan, complete the cycle the facility and the community started. There are several types of exercises and each has its use, but no single exercise can adequately test all of the elements of an emergency management system. Properly implemented, an ongoing exercise program will:

- Help evaluate emergency plans and response capability;
- Provide the information necessary to improve plans and procedures;
- Train the participants;
- Improve coordination between on-site and off-site personnel;
- Ensure the continued involvement of key community organizations;

- Provide a way to inform and involve the public and the media; and

- Serve as a visible demonstration of industry and community commitment to protect the public.

Facility Management Role--

Facility management has a pivotal role. Exercises are complex events that require the cooperation of many people and organizations. Without the active support and encouragement of the chief executives of these organizations, there is little chance for success. The most important parts of the task are committing the necessary time and resources of the organization and gaining the cooperation of the chief officials in the community.

Components of the Program--

Four types of exercises should be the major components of the program:

- Tabletop;

- Emergency operations simulation;

- Drill; and

- Field exercise.

They range from the simple to the complex and each has a definite function.

Most industrial managers are familiar with the concept of a drill or field exercise. Such exercises typically involve actual response by personnel and the use of protective equipment, emergency apparatus, and field communications. A drill focuses on a single aspect of an emergency response system, while a field exercise tests all or most of the response system.

The tabletop and emergency operation simulation exercises are less commonly used and are characterized by the simulation of all or most of the actions to be performed in emergency response. They provide substantial benefits within an overall exercise program because they are usually less complex and require less time and effort to plan and conduct. They are also more flexible as learning experiences and can build confidence and capability for more involved exercises.

- A tabletop is primarily a learning exercise that takes place in a classroom or meeting room setting. Situations and problems generate discussion of plans, procedures, policies, and resources. Tabletop exercises are an excellent way to familiarize a group of organizations and agencies with their assigned roles. This type of exercise is also a good method for testing the logic and content of the plan. It is sometimes referred to as a "What if" exercise.

- An emergency operation simulation (EOS) is a full-scale emergency simulation that uses various forms of message traffic (telephones, radios, message forms, etc.) to create a realistic, high-pressure, emergency environment. EOS exercises stimulate decision-making and interaction by emergency managers in response to simulated emergency conditions. An EOS is conducted in an Emergency Operating Center or in another suitable facility and involves command, control, and decision making functions. All field response activities are simulated, with activity limited to the controlled environment of the facility used. They are very useful for testing direction and control functions and for evaluating how well the total response system is coordinated.

- The drill is a supervised activity that tests, develops or maintains skills in a single emergency response function (i.e., communications drills, fire drills, command post drills, medical emergency drills, etc.). These frequently involve actual field response, activation of emergency communications networks, and equipment and apparatus that would be used in a real emergency. The effectiveness of a drill is its focus on a single, or relatively limited, portion of the overall response system in order to evaluate and improve it.

- A field exercise practices all or most of the basic functions of the response system simultaneously and the ability of the different organizations to work together. A full field exercise involves at least a partial mobilization of each organization's resources and a demonstration of their response actions. It also includes activation of all emergency facilities, including emergency operations centers, communications centers, command posts, hospitals, media centers, first response units, etc. A field exercise may exclude some specific functions previously tested, but it should include all response functions that require significant coordination with any others being tested.

Table 2-2 summarizes some of the advantages and disadvantages of each type of exercise.

TABLE 2-2. EXERCISE TYPES--ADVANTAGES AND DISADVANTAGES

Advantages	Disadvantages
1. Tabletop Exercise	
Modest time, cost, and resource commitment. Effective method of reviewing plans, procedures, and policies. Good training for key personnel in responsibilities and procedures. helps build coordination and consensus.	Lacks realism. Does not provide a true test of emergency system operation.
2. Emergency Operations Simulation (EOS)	
Moderate time, cost, and resource commitment. More realism than a tabletop exercise. Tests integrated response of entire emergency management system. Good method of testing command and control before "going public."	Heavily dependent on written scenario. Realism/effectiveness can suffer when not well planned and executed.
3. Drill	
Moderate time, cost, and resource commitment. Easiest exercise to design. May be very realistic. Provides good hands-on training. Allows a single component of the system to be isolated and practiced in depth.	Does not test entire system. Player safety is critical.
4. Field Exercise	
Good realism. Good test of integrated communications. Provides means to evaluate mobilization of resources and first responder capability. Good opportunity to increase public awareness of program.	Major time, cost, and resource commitment. Scenario development is very critical. Player/public safety is critical. Can create problems when poorly planned.

2.4 REFERENCES

1. U.S. EPA Chemical Emergency Preparedness Program, Interim Guidance, Revision 1, 9223.0-1A, November 1985.

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3. Chemical Manufacturers Association, CAER Handbook, Washington, D.C., 1985.

4. Lees, F.P. Loss Prevention in the Process Industries, Vol. 2, Butterworth's, London, England, 1980.

SECTION 3
FACILITY SITING AND LAYOUT

The consequences of an accidental release can be reduced by incorporating mitigative features into the design of a facility's layout and siting. Siting is the location of the process facility within a community or region, while layout is the positioning of equipment within the process facility. Although it is important to consider siting and layout when designing a new facility, the guidelines discussed in Subsection 3.2 apply equally to facility expansions. Siting could also be an important factor when deciding whether to expand a particular facility.

3.1 BACKGROUND

Siting and layout design principles that can reduce the effects of an accidental release include the following:

- Locating the facility within the community or region in a way that reduces the number of people that could be affected; and/or
- Arranging equipment within the facility in a way that reduces the effect that a potential release from one location within the facility would have on the rest of the facility, or on the surrounding community.

One study of the contribution of different hazard factors to accidental releases found that poor facility siting played a role in 5.8% of the cases and that poor facility layout was a factor in 3.9% of the cases (1). The study did not distinguish between factors that could have prevented the incident and those that could have mitigated its effects. Although this section focuses on the mitigation of accidental releases, the information presented in Subsections 3.2 and 3.3 may also help prevent the occurrence of an accidental release. Preventive measures for facility layout and siting are discussed in the Control Technologies Manual of this Prevention Reference Manual series (2).

3.2 SITING

Siting refers to the location of the process facility within a community or region. Often, siting is carefully examined only for new facilities; however, the expansion of an existing facility may require a reevaluation of the site to assess the suitability of the expansion. This will be especially true if the expansion involves chemicals or processes that pose more hazard than presented by the original facility. One author discusses siting from a process hazard perspective and cites a number of references (3).

A study of factors that have contributed to losses in several hundred large fires and explosions identified the following inadequacies in facility siting: poor utility service; poor emergency response and fire protection; off-site traffic congestion hindering response by emergency vehicles; and poor drainage (1). The effect of these inadequacies can be magnified by meteorologic factors and population densities around the facility, two factors that will determine the effects of an accidental release on off-site populations (3,4).

Literature on chemical facility siting has generally been limited to discussions of traditional siting criteria, i.e., distance from raw material resources and markets and suitability of the transportation system and utilities (5,6,7). However, the siting of facilities such as nuclear power plants and hazardous waste disposal units has been more problematic historically, and specific siting criteria have been developed to address public and environmental health issues in these industries. Some of the issues identified in the related literature could be relevant to the siting of a chemical facility that uses or produces toxic chemicals.

3.2.1 Population Density Near Facility Site

Clearly, the fewer people that live near an industrial facility, the fewer that would be affected by an accidental release. One way to minimize the number of people affected by a potential accidental release is to maintain a buffer zone immediately around or downwind of the facility. The buffer zone for a nuclear power facility, for instance, is a circle with a 0.3 to 1.3 mile radius (6). A distance of five miles downwind was required during the siting of a spill test facility for liquefied fuels, ammonia, and chlorine (4). Setting aside a controlled buffer zone, however, has not been standard practice in industrial facility siting. Although industrial facilities may be sited in what is initially a rural area, the facility itself may become the focus of later development; therefore, setting aside a buffer area is one way for a hazardous industrial facility to protect itself against the problems of future urbanization.

Another way to reduce the population density around a facility is to maximize the distance to population centers. This issue has not been explicitly addressed in the siting of hazardous industrial facilities. The site of the Bhopal Union Carbide facility, where a MIC release resulted in over 2,000 deaths, was found in 1975 to be "not suitable for hazardous industries" because of the population density around the facility (8). Two hundred thousand people lived within a 4-mile radius (9). The facility did, however, receive approval to operate despite this evaluation. Contrast this with siting requirements for commercial nuclear power reactors or hazardous waste disposal facilities. The New Jersey hazardous waste facility siting act requires a minimum distance of 2,000 feet between the facility and the closest residence or school. For some types of hazardous waste disposal facilities, a half mile distance from residences or schools is specified (10).

The regulations governing commercial nuclear reactors take a different approach to specifying distances from population centers. The regulations specify two zones, calculations of which are based on maximum exposure from a major accident and a population center distance. The population center distance is the distance to the nearest densely populated center with more than 25,000 residents. The population center distance must be at least one and a third times the distance from the reactor to the outer boundary of the second zone (11). Thus, the distance to the population center will be a function of the design of the facility and the definition of a major accident.

Increased distance from population centers also allows more time to respond to an emergency and evacuate or inform the local population. This relationship is addressed indirectly by the nuclear plant siting regulations discussed above. However, the literature does not examine the relationship between time available for emergency response and facility distance from population centers. Clearly, the distance could not be fixed arbitrarily, but would be a function of factors such as emergency preparedness and population mobility (i.e., access to public transportation, cars per household, road network).

An example of a risk-based approach to facility siting can be found in the Canvey study, an investigation of a heavily industrialized area in England (12). The study examined existing and proposed facilities in the Canvey Island/Thurrock area and calculated the individual and total risk posed by the petrochemical and shipping facilities to area residents. The Commission recommended that the proposed facilities be approved on the condition that risk reduction measures be undertaken by the existing facilities. The Canvey study illustrates how quantitative risk analysis can be used during the facility siting process. This type of approach would be especially suited to facility expansion decisions.

The literature on the siting of hazardous industrial facilities does not provide guidelines as to what constitutes a safe distance or an effective buffer zone. Examples of buffer zones considered during the facility siting process are given in the literature about other fields, but these examples may not directly apply to chemical processing facilities.

3.2.2 Meteorology and Climate

Meteorologic considerations involve identifying the prevailing wind direction, wind speed, and atmospheric stability. Meteorologic data can be used to rule out inappropriate facility sites or to locate units within the facility boundaries. Hazardous units should be located to minimize the effects of a release on off-site and on-site populations and should be downwind (for the prevailing wind direction) from major population concentrations when possible.

Wind patterns can be characterized in three ways. One is the large-scale movement of major air pressure systems. An intermediate scale involves air movements caused by regional topograhic features and differential heating. A more local effect can be caused by the presence of ridges and valleys. Data on all three types of patterns may be used to predict areas affected by accidental releases (4). However, of most interest will be site-specific wind characteristics. For example, ridges and valleys may channel surface winds that would carry heavier-than-air releases. Ridges serve as barriers in this instance; whereas valleys are possible conduits for the accidental release. The reader is referred to Section 5 on dispersion modeling and Section 6 on meteorological instrumentation for a discussion of the use of meteorological data and the modeling of release impacts.

Temporal variability in wind direction may occur daily or seasonally. Temporal variability may be an important characteristic when there is a basis for determining the most likely time for a release; for example, if the chemical is only stored or processed on site for a specific period. Otherwise, it could be assumed that the most frequently occurring wind direction is the one of greatest interest in modeling impacts. However, it will often be necessary to investigate the effects of other than prevailing wind conditions.

Examples of accidental release incidents in which the meteorological conditions aggravated the release's impact can be found in the literature. At Bhopal, for instance, the area was experiencing an atmospheric inversion at the time of the release. An inversion increases the time needed to disperse a chemical cloud to safe levels. A region that experiences inversions frequently may not be an appropriate site for a hazardous industrial facility. Other incidents in the literature illustrate how unstable or neutral atmospheric conditions are beneficial, since the wind movement disperses dangerous concentrations quickly; see case history A-24, Lees (3). Another example of basing the selection of a site on good dispersion characteristics (reliable wind direction and wind speed) can be found in Miller, (4).

3.2.3 Emergency Response

A rapid response by facility or local emergency response personnel can mitigate the effects of a release. If a facility is to be located in an area that does not have an adequate emergency response system or if the addition of the facility will strain the area's emergency response capabilities, the facility owners might consider giving support to local emergency response services. New Jersey now requires this of major hazardous waste facilities. The New Jersey hazardous waste facilities siting act specifies that five percent of a facility's gross receipts will be paid to the host municipality for the cost of additional emergency response training and equipment (10). Several chemical companies also report supporting the emergency response capabilities of host communities (6).

3.2.4 Topography and Drainage

A fairly level site is necessary to prevent flammable liquids from flowing down a sloped terrain to other equipment or buildings. Also, the facility site should not drain highway runoff, since flammable liquids from a highway accident may spread a fire. Hills may be used as natural barricades, separating operations with potentially explosive chemicals (13). The effect of the terrain on wind patterns should be considered also, since local features such as valleys and ridges will channel winds. Hills or ridges can also block, divert, and help disperse an air release of a toxic chemical.

3.2.5 Accessibility to Off-Site Emergency Response Vehicles

If the facility is to be served by off-site emergency response personnel, it must be easily accessible. Facility entrances should be free of traffic congestion or blockage by trains (moving, stopped, or derailed); the facility should have multiple entrances/exits, ideally onto different streets or roads so that one accident cannot block all escape routes (13). It should also be considered whether the facility site is accessible year round. In areas with snow and ice, reliance on measures in addition to or instead of outside emergency response services might be warranted.

3.2.6 Utility Service

Water, gas, power, and any other utilities should be reliable. An adequate supply of water for fire fighting is essential. Failure of several utilities services simultaneously can aggravate a release incident (13). Water and electricity are the most important utilities, since they are essential to fire fighting, cooling systems, operation of pumps, lighting, and instruments, etc. Back-up electrical power and looped water mains are typical safeguards. A looped water main originates at a source, is routed through the facility and then returns to the source. This arrangement allows water to flow from the source in either direction through the loop. Thus, a break in the line at any point will not cut off the rest of the loop from the water source.

3.3 LAYOUT

Layout concerns the placement and spacing of the components of a process facility, including the individual equipment in each component. A properly designed facility will minimize the consequences of an accidental release by facilitating process operability and by segregating hazardous areas. Both the Chemical Manufacturers Association (CMA) and the National Fire Protection Association (NFPA) have issued standards and guidelines for facility layout (14). Key features to be considered during the layout of a facility site are its boundaries, the work boundaries, through railway lines, ignition sources, control rooms, buildings that concentrate personnel, production units, storage, loading and unloading, pipebridges, roadways and waste disposal areas.

A study of factors that have contributed to losses in several hundred large fires and explosions identified hazard factors and grouped these into nine categories. Problems with facility layout and spacing were characterized in the following way: congested process and storage areas; lack of isolation of extra-hazardous operations, lack of proper emergency exit facilities; sources of ignition too close to hazardous critical facility areas; and inadequate hazard classification of facility areas (1). These problems can be addressed by applying the general principles discussed below.

3.3.1 Adequate Spacing Between Units

It is important to increase the distance between process units to reduce the impact of an accidental release. An explosion in one process unit can result in an accidental release in another unit because of damage from the blast wave. The blast wave pressure front travels rapidly, but its intensity decreases rapidly with distance. A vapor cloud associated with an accidental release travels much more slowly than does a blast wave but usually affects a larger area before it is diluted enough to present no danger. Explosions of vapor clouds can be particularly destructive in congested plants.

A quantitative method may be used to specify the spacing between facility units. First, a relative hazard ranking is developed of the individual process units, including manufacturing units, unloading/loading operations for tankers or drums, major pipebridge sections and major cross-country pipelines. One common method of quantifying the potential fire and explosion hazard of a given process unit is the Dow Index (15). The Dow Index has been modified to address the potential hazards of toxic chemical releases. This Mond Index is one of several methods developed for quantifying spacing requirements between facility units (15,16). Other methods for quantifying spacing requirements have also been developed (15,16).

Safe spacing requirements can be developed for a particular site, as described above, or reference may be made to published sources, a number of which recommend minimum safe separation distances for process and storage units. Reference 3 lists several other sources that discuss safe separation distances. Reference 3 notes that most of the published guidelines for spacing requirements give little explanation of the basis for the distances and that many sources incorporate recommendations from each other.

The two principal factors that have been traditionally used for determining safe separation distances are: 1) the heat produced by the burning liquid and 2) the potential to ignite the accidentally released gas or vapor. Separation of units from identified ignition sources, such as furnaces, electrical switchgear, flarestacks or transport vehicles is one of the most common recommendations encountered in the literature. A review of case studies in Reference 3 shows that the presence of an ignition source near an accidental release source can turn an initial release incident into a fire that can cause a greater loss of life and property. For instance, in the Feyzin refinery case cited in Reference 3, a source 160 meters distant from the plant unit is suspected of igniting a cloud of propane. Note that the toxic hazard associated with an accidental release may be more severe than the hazards associated with its heat of combustion or flammability. In such cases, traditional methods of determining safe separation distances may not be appropriate.

Some special considerations adapted from the literature for the safe spacing of facility units are:

- In general, units with the most toxic materials should be suitably distant from all facility buildings containing appreciable concentrations of personnel, and also from activities outside the works boundary. This particularly applies to off-site population centers such as schools, hospitals, places of entertainment, etc.

- Units having the greatest potential for explosion should not be located close to a facility boundary; they should be separated by areas occupied by low-risk activities with low population densities (up to 25 people per acre).

- Independent elements should be spaced so that a fire or explosion in one unit has a minimum effect on other units. When units cannot be adequately spaced and segregated, the use of barricades, protective construction, and fixed fire protection is recommended. For further information see Rindner and Wachtell (18) and Lewis (17).

- Ignition sources, including trucks, railroads, boilers, personnel smoking areas and direct-fired equipment should be located away from and upwind of hazard areas processing or storing flammable liquids, gases, or vapors. Some standards call for at least 10 feet of separation between vapor hazard areas and ignition sources, although this distance may be reduced by using vapor barriers or other special protective systems (13). Yet in the Feysin refinery example, the ignition source was thought to be 530 feet away, which illustrates the importance of evaluating each situation individually and identifying high-hazard areas.

- Facility work units should not be located at the facility boundary. Distance to the facility boundary will vary, depending on the hazard of the unit (17).

Finally, the initial design must allow sufficient space for future facility expansions, and the expansions must also adhere to safe layout principles.

There are two schools of thought on the safest spacing of interconnected process units. One, which emphasizes the danger of individual process units and specifies minimum safe distances between types of units, focuses on the dangers of fire and explosion. Another school of thought emphasizes the danger of releases from long pipe runs and considers specific maximum spacing between the units to minimize such long runs. This approach applies more to non-flammable, acutely-toxic materials. In many cases, both fire and toxic release hazards are present and spacing design will be a compromise between them. Both hazards can be addressed by planning for enough space (to satisfy fire/explosion concerns) and by breaking up the resulting long pipe runs with several emergency excess flow valves (to reduce the size of a release if the pipe should rupture at any point).

3.3.2 Grouping or Isolation of Facility Units

How units are arranged within the facility is important, since this partly determines whether the initial accidental release remains localized or spreads throughout the facility processes. General guidelines for locating units within a facility are noted below (13,17):

- Whenever possible, high hazard-units should be separated from each other by units of mild, low, or medium hazard.

- Control rooms, amenity buildings, workshops, laboratories and offices should be adjacent to units of mild or low hazard, which act as a barrier from higher-hazard units. Medium-hazard units are only acceptable adjacent to populated buildings (a) if lower-hazard units are not available to separate them, and (b) if the hazard level is only just inside the "medium" band of overall hazard rating, as assigned by the Mond Index.

- Storage units, such as tanks and container storage areas, should be adequately separated from operational areas and, as far as possible, located away from road and rail traffic routes within the plant site.

- Major pipebridges with a medium to high overall hazard rating assigned by the Mond Index method should be protected from accidents that could happen on tall process units and from vehicle collisions. Incidents on tall process units can spread by the collapse of the tall unit onto adjacent pipebridges.

3.3.3 Transportation

Planning an adequate transportation system is an integral part of plant layout. An adequate transportation system mitigates the effects of an accidental release in two ways: 1) emergency responsiveness depends on ready access to the affected units to reduce the spread of the emergency in the plant, and 2) a timely evacuation of potentially affected populations reduces the number of people affected. Design principles of an adequate transportation system are described below (13,17).

- Roads should allow entry to the facility from at least two points on the site perimeter, preferably from opposite sides and onto different roads/streets.
- All units in the facility with a moderate or high fire risk should be accessible to for emergency vehicles from at least two directions.
- Control rooms should have access to an easy exit, since control room personnel may be the last plant personnel to leave the facility site.
- Facilities with access from heavily traveled super-highways should also have alternative emergency entrances.

3.3.4 General Layout

A few other recommendations appear below (13,17):

- Control rooms, amenity buildings, workshops, laboratories and offices should be close to the site perimeter and away from hazardous storage and process areas.

- Pipebridges should be laid out to minimize the transfer of accidents from one unit to another. Key pipebridges should be assessed individually for hazard potential, independently of adjacent units.

- As far as possible, units should be laid out for a logical process flow to minimize the pipebridge requirements.

- Pipebridge routes should be chosen so that they are not likely to contribute to the spread of an accident. Alternative routes should be selected to retain as much process control as possible to be retained in the event of an incident occurring.

- A rectangular block layout is often used for chemical and petrochemical plants so that emergency response vehicles can gain access to all units. Roads can also act as a fire break.

- Water systems should be adequate in all parts of the facility. For a larger facility, the water system may consist of a number of loops, rather than one large loop.

- Sewers and drainage should be laid out to allow rapid and safe removal of spilled chemicals and water used in fire fighting.

- Critically important facility elements (power plants, computer and control rooms, special process units) should be given maximum protection, which might include extra space dividing them from other units, proper location, or barricades.

- Hazardous units in the facility should be accessible to fire stations and other emergency facilities.

- Waste disposal and hazardous units processing, storing, or disposing of toxic gases and liquids should be located downwind of concentrations of people on site and off site.

For a detailed discussion of facility layout, refer to Lees (3) and Mecklenburgh (19).

3.4 COSTS

The cost of incorporating mitigation measures into facility siting and layout cannot be estimated quantitatively since the costs will be specific to the site. A general discussion of the types of costs to be encountered is presented here.

Mitigation measures such as increased spacing between units increase facility construction costs in two ways. Most directly, the facility might require additional land to create adequate spacing between all units. Also considered a mitigation cost is the additional expense of longer piping and utility runs within the facility. Additional spacing between units will result in increased pipe length and longer utility lines.

Directly measurable are the costs of including additional land as a buffer for the facility, which is a function of land prices and of the size of the area designated as a buffer.

It is difficult to estimate the cost of designing mitigation measures into the facility siting without considering a particular site and facility. Sites rated high according to mitigation criteria (i.e, not upwind of a populated area, for example) would not necessarily cost more to develop than sites selected according to traditional criteria. However, the initial site cost is only a portion of the facility costs. If transportation costs increase because of a greater distance to market, there is a direct cost to the firm for locating the facility in the site selected for mitigation purposes. To evaluate the overall effects mitigation will have on costs, an analysis of the facility's construction and operating costs would be needed. Comparing the total costs at two sites, one selected according to mitigation criteria, the other according to traditional siting criteria, is a way to determine how the incorporation of specific mitigation measures affects overall costs.

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SECTION 4

DETECTION AND WARNING SYSTEMS

Detection and warning systems are widely used in the chemical process industries to alert plant operators and personnel of process upsets and potentially hazardous situations that could lead to loss of production, property, or in the extreme case, human life. Common to most chemical processing facilities are detection and warning systems built into the process control systems. Such systems monitor process operating conditions such as the temperature, pressure, and flow rate, and trigger audible and visual alarms when these process variables exceed design limits. Other detection systems identify hazards after a release from a process or storage tank has occurred. These systems may detect leakage of the chemical itself, flame, heat, smoke, or gaseous products of combustion (1,2). Plant personnel also play a role in detecting and warning of hazardous releases. However, in the absence of a visible plume or fire, the reliability of plant personnel depends greatly on the particular material being released, ambient conditions, and the individual's physical senses. Reliance on plant personnel for detection and warning can result in dangerous exposure of plant personnel to hazardous materials. Visual observations, however, either directly by personnel in the vicinity of the release or by personnel monitoring closed-circuit television systems, can provide information on the direction and speed of a hazardous release (3).

This section discusses systems used to detect and quantify concentrations of leaks or releases of chemicals to the atmosphere after the release occurs but before an actual fire and/or explosion. Because of the large number of sampling and analytical methods available for collecting and analyzing hazardous gases and vapors, the discussion is limited to direct reading instruments or indicators, which, along with their sensing elements, can yield test results in the short time needed to quickly respond to a hazardous release incident. Post release detection systems are important because the more quickly an airborne release of a hazardous material is detected, the greater the opportunity to minimize the effects on the community by implementing on-site and off-site emergency response procedures.

4.1 BACKGROUND

The purpose of a gas or vapor detection system is to provide a quantifiable indication of the concentration and location of a released chemical that could lead to fire, explosion, or exposure of facility personnel or the general public to hazardous concentrations of an airborne chemical. With adequate warning from an automatic or manually operated warning system, facility personnel and off-site emergency response personnel can take appropriate action to reduce the effects of the chemical release. Specific mitigation procedures taken in response to a leak or release are discussed in other sections of the manual.

The general types of gas detection systems include (1,4,5):

- Multiple devices for sampling the air at various points throughout the facility, using vacuum pumps and tubing which then convey the sample to a common analyzer;

- Portable sampling/analyzing/monitoring devices that are battery or manually operated and carried by plant personnel to determine the concentration of a gas at a particular point of interest in the facility;

- Devices where the sensing element and readout are contained in a single unit mounted in the area of the hazard;

- Multiple sensing elements wired to a single control panel located at a point remote from the area being monitored; and

- Remote optical systems.

These systems often include an audible or visual alarm that activates when it detects a release (2). Audible alarms include bells, whistles, sirens, horns, or easily understood voice messages. In high-noise areas, visual alarms in the form of lights are often used.

Once an alarm signals that a fire or release has occurred, the emergency must be analyzed, and facility field personnel and/or the process operator in the control room must take appropriate action to manually control the release. In some cases, the detection system may activate mitigation devices such as steam curtains or automatically released firefighting agents (1). A fully automated computer system may be able to detect the release, determine whether the release constitutes a hazard, display the location of the release, sound warning alarms, provide instruction concerning mitigation of the release to the operator, or automatically engage control devices, and telephone emergency messages to the surrounding community public service agencies (1,2,3). However, the danger and the damage that could occur if emergency response procedures were falsely activated means that an automated system must be highly reliable.

4.2 DESCRIPTION

Detection instruments use a variety of operating principles, including (6):

- Electrical conductivity, potentiometry, calorimetry, and ionization;

- Radioactivity;

- Thermal conductivity and heat of combustion;

- Electromagnetic methods such as infrared photometry, ultraviolet photometry, and other photometric methods;

- Chemi-electromagnetic such as colorimetry and chemiluminescent methods;

- Magnetic methods such as paramagnetic analysis and mass spectroscopy; and

- Gas chromatography.

In cases where releases of toxic chemicals occur at remote locations, such as during transportation accidents, direct reading colorimetric indicators are sometimes used for qualitative and quantitative measurements of the released chemical. Methods include liquid reagents, chemically treated papers, and glass indicating tubes containing solid chemicals that change color and/or exhibit a length of stain that can be compared with a standard to determine the concentration of the toxic gas (7). These types of manually operated indicators are used in addition to other direct-reading instruments based on the principles previously cited (8).

A detailed description of the numerous detection principles and instruments available for detecting flammable and/or toxic gases is included in References 6, 7, and 8. The following subsections are summary discussions of the types of instruments typically used to detect flammable and hazardous gases associated with an accidental release.

4.2.1 Combustible/Flammable Gas Detectors

Combustible/flammable gas detectors are commonly used to measure the lower explosive limit (LEL) or lower flammable limit (LFL) of flammable gases in air. (According to Reference 1 the terms are used interchangeably.) The below which the mixture cannot be ignited to yield a self-sustaining flame (9). Examples of detectors are catalytic combustion sensors, solid-state electrolytic sensors, and infrared analyzers (10). Table 4-1 presents the characteristics of these and other combustible/flammable gas detection systems.

Catalytic combustion sensors use a sensing element such as an electrically heated platinum wire across which a sample of gas is drawn. The flammable gas burns on the wire, which produces heat in direct proportion to the concentration of the flammable gas in the air. The temperature of the wire changes the electrical resistance. Electronic circuitry in the instrument creates a readout indication as a percent of the LEL or percent concentration. If the LEL is exceeded, alarm circuits and warning signals may be activated to alert personnel of dangerous concentrations of gas in the vicinity.

In a solid-state electrolytic sensor, the gas diffuses into the sensing element (a semiconductor), resulting in a decrease in the electrical resistance of the cell (10). The current flow resulting from this diffusion is related to the concentration of the gas in the air, which is shown on a meter as percent LEL.

Infrared analyzers draw air samples into a cell where an infrared light shines perpendicular to the flow of the liquid. A detector on the side of the cell opposite the light source measures the intensity of the light. The gas of interest absorbs infrared radiation at a certain wavelength ranging from 2 to 15 micrometers (10,11). Thus, the concentration of the gas in air will be proportional to the amount of infrared light absorbed. Two types of infrared analyzers are available: the nondispersive type that operates at a specific wavelength, and the dispersive type that can operate at several different wavelengths. Infrared analyzers may draw air samples from several locations or they may be set up to monitor only one location.

TABLE 4-1. COMPARISON OF CHARACTERISTICS OF VARIOUS COMBUSTIBLE/FLAMMABLE VAPOR DETECTION TECHNIQUES

	TECHNIQUE						
Characteristic	Gas Chromatography	Hydrogen Flame Ionization Detector	Thermal Conductivity	Interferometry	Infrared	Semiconductor[a]	Catalytic Combustion
Sensitivity	Excellent	Best	Poor to Good	Good	Very good	Excellent	Very good
Reliability	Good	Good	Good	Good	Good	Poor	Very good
Selectivity	Excellent	Very Good[b]	Poor to Good	Poor[c,d]	Very good[b]	Poor[d]	Very good
Response time	Poor	Good	Good	Good	Good	Excellent	Excellent
Stability	Good	Very Good	Poor to Good	Good	Very good	Good	Good
Simplicity	Very complex	Medium complexity	Simple	Medium complexity	Medium complexity	Very simple	No
Sample system required	Yes	Yes	Yes	Yes	Yes	No	Very simple
Relative cost	Very high	Medium to high	Medium	Medium	Medium	Low	Low
Rangeability	ppm. to 100%	ppm. to low %	Wide	Wide	Very Wide	Very wide	Below UEL[e]
Maintenance	High	Medium	Medium	Medium	Medium	Low	Low
Auxiliary gas supplies	Yes	Yes	Sometimes	No	No	No	No

[a] Diffusion head type sensor.

[b] Will not detect hydrogen.

[c] Hydrocarbons and hydrogen of opposite polarity signals.

[d] Responds to products of emission.

[e] Upper explosive limit.

Source: Reference 5.

4.2.2 Toxic Vapor Detection Systems

Detecting toxic vapors requires much greater sensitivity than is required for detecting flammable vapors. Detection systems for toxic vapors often rely on detectors that respond to a specific chemical. Less often, a single device can be used to monitor a variety of hazardous vapors. These devices measure the concentration of the toxic gas and allow the operator or automated system to compare the measured value with some set ceiling value. If this concentration value is exceeded, an alarm system is activated.

The design of detection systems is based on a number of principles and methods, including optical absorption, photoionization, flame ionization, mass spectroscopy, gas chromatography, pH, measurement, and infrared spectrophotometry (12). Detailed descriptions of operating principles and available instruments appear in References 6, 7, and 8. Before committing to any type of detection system, discussions should be held with equipment vendors or manufacturers to determine the correct application of the detection device to the vapors or gases to be monitored. For vapors and gases with both a lower explosive limit (LEL) and an employee exposure limit, an instrument capable of measuring the LEL may not be appropriate for measuring the exposure limit concentration. The LEL may cover only a single decade of vapor concentrations, for instance 1 to 10 percent, while the toxicity-based exposure limit may include concentrations from fractions of a part per million (ppm) to several thousand ppm (5). The wide range of concentrations may require different types of detection systems.

For example, Table 4-2 lists the various types of instruments available from one manufacturer for monitoring several toxic gases. A survey instrument is typically a portable, battery-powered device used to locate leaks or to measure ambient concentrations of toxic gases for a short time. Personal sampling instruments are devices that are typically worn by personnel who may be exposed to high concentrations of toxic gases. These devices are usually equipped with alarms to warn the wearer when dangerous concentrations are

TABLE 4-2. EXAMPLES OF INSTRUMENTS AVAILABLE FOR VARIOUS TOXIC CHEMICALS[a]

Substance	Survey Instrument	Personal Sampling Instrument	Area Monitoring Instrument
Ammonia	Autospot	-	PSM-8 Multipoint Monitor, PSM-8e Multipoint Monitor, Series 7000 Continuous Monitor, Series 7100 Continuous Monitor
Chlorine	Autospot	Monitox/Chronotox	PSM-8 Multipoint Monitor, PSM-8e Multipoint Monitor, Series 7000 Continuous Monitor, Series 7100 Continuous Monitor, Statox Multipoint Monitor
Hydrazine	Autospot	Monitox/Chronotox	Series 7000 Continuous Monitor, Series 7100 Continuous Monitor
Hydrogen Cyanide	Autospot	Monitox/Chronotox	PSM-8 Multipoint Monitor, PSM-8e Multipoint Monitor, Series 7100 Continuous Monitor, Statox Multipoint Monitor
Hydrogen Fluoride	-	-	PSM-8e Multipoint Monitor, Series 7100 Continuous Monitor
Hydrogen Sulfide	Autospot	Monitox/Chronotox	PSM-8 Multipoint Monitor, PSM-8e Multipoint Monitor, Series 7000 Continuous Monitor, Series 7100 Continuous Monitor, Statox Multipoint Monitor, Statox E Multipoint Monitor
Phosgene	Autospot	Miniature Continuous Monitor, Monitox/Chronotox	PSM-8 Multipoint Monitor, PSM-8e Multipoint Monitor, Series 7000 Continuous Monitor, Series 7100 Continuous Monitor, Statox Multipoint Monitor
Sulfur	Autospot	-	PSM-8 Multipoint Monitor, PSM-8e Multipoint Monitor, Series 7000 Continuous Monitor, Series 7100 Continuous Monitor
Toxic Vapors (General)	Vacu-Sampler	Accuhaler, Low Flow, Sampling Pump	-

[a] Note: The instruments listed are manufactured by MDA Scientific, Inc. Their listing does not constitute an endorsement.

reached. Area monitoring instruments are designed for continuous monitoring at fixed locations. A single area monitor can sample several locations if a switching valve and a sampling manifold are used.

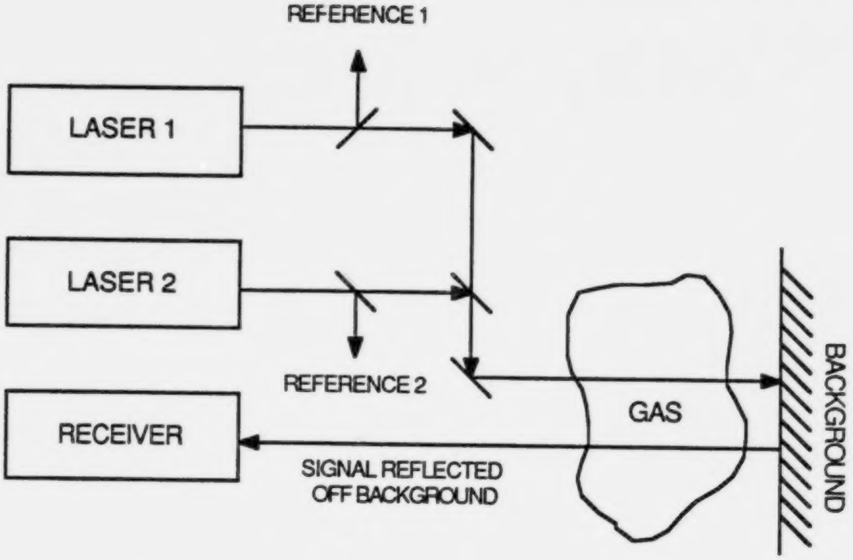
4.2.3 Remote Monitoring

The previous detection methods are applied at a specific single location or set of locations within a facility. However, a number of techniques have been developed for remotely detecting hazardous vapors and gases. Remote detection uses sensors not physically located at the point of release or in the area directly covered by the plume or cloud.

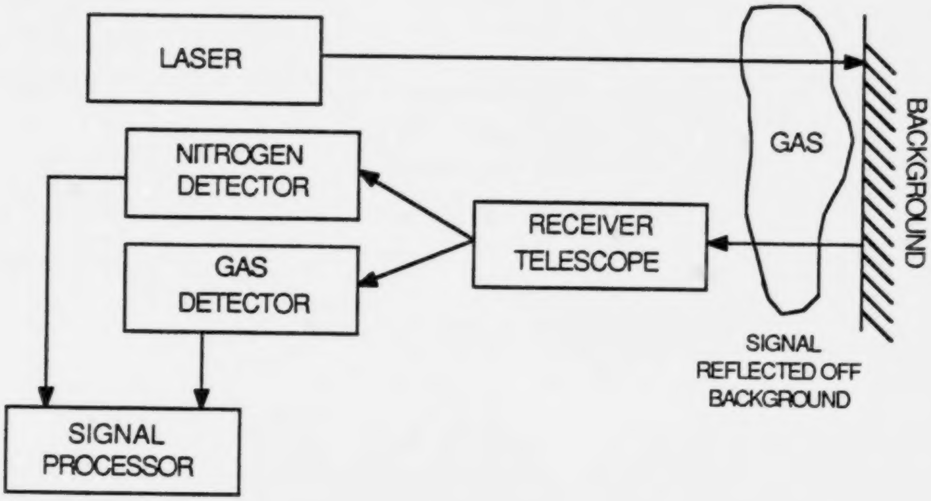
Most of these systems use some form of light beam directed through the plume or cloud. These detectors cover an area rather than a single location. A variety of remote detection systems are available (4,8). Two of the most widely used laser-based optical monitoring technique are the Differential Absorption Light Detection and Ranging (LIDAR, also abbreviated as DIAL) and the Raman LIDAR remote detection technique. Figure 4-1 is a schematic representation of these systems.

The DIAL technique uses two lasers at different wavelengths. The first wavelength coincides with band peak of the target gas and the other coincides with a band where the gas does not absorb. The lasers are positioned so that scattered or reflected light from natural or positioned targets is detected by a receiver, which determines the concentration of the target gas by comparing the wavelengths of the reflected light (since the concentration is proportional to the difference between the return signals at the two specified wavelengths).

The Raman LIDAR technique differs from the DIAL technique in that only one laser beam is used. The advantage of this technique is that the beam does not have to be tuned to any specific wavelength. Operation of the Raman LIDAR technique is based on the phenomenon that light scattered by gas molecules


REFERENCE 1
LASER 1
LASER 2
REFERENCE 2
RECEIVER
SIGNAL REFLECTED OFF BACKGROUND
GAS
BACKGROUND

DIAL remote detection system


LASER
NITROGEN DETECTOR
GAS DETECTOR
RECEIVER TELESCOPE
SIGNAL PROCESSOR
GAS
BACKGROUND
SIGNAL REFLECTED OFF BACKGROUND

Raman LIDAR remote detection system

Figure 4-1. Schematic representations of typical remote monitoring techniques for hazardous vapors.

produces a shift in wavelength. The wavelength shifts that occur are independent of the incident wavelength and are characteristic of specific compounds. Signals reflected off a background are collected by a receiving telescope and are sent to a detector for concentration determination. The Raman frequency of nitrogen in the air is used as a reference frequency, which allows the system to discriminate between scattering from the target gas and that from other atmospheric compounds.

References 4 and 8 discuss in more detail these and other remote detection systems.

4.3 DESIGN

The design of an effective detection and warning system for hazardous vapor releases must consider the following (5,13,14,15):

- Selection of the proper detection equipment (for the vapor of interest and its particular hazard) which meets the appropriate code or is approved for use within the facility environment;
- Location of sampling points and positioning of detectors;
- Installation of the detection system;
- Type of alarm system; and
- Maintenance, checking, and calibration.

The selection of equipment is based on the likely concentrations of the specific chemicals to be detected. In some situations, combinations of devices might be required. The selection process should include information from equipment manufacturers and require certification that the equipment will perform properly in the given application.

Equipment used should meet the National Electrical Code and have Factory Mutual, Underwriters Laboratory, Canadian Standards, or Bureau of Mines approval for use in Class 1, Division 1, Group A,B,C, and D classified areas (14).

Detector and sampling points should be located either around the perimeter of a potential source or at the source. Sources may include pumps, valves, flanges, compressor seals, rupture discs, vents, pressure relief valves, storage containers, stacks, and ventilation and air conditioning system intakes (5,14). The location of detectors or sampling points should take into consideration the local wind conditions and structures that may affect air flow in the immediate vicinity of the source. Multiple detectors should be located no more than 30 feet apart (13). One reference suggests that sampling points or detectors should be located 1-1/2 feet above ground for heavier-than-air combustible compounds and 6 to 8 feet above ground for lighter-than-air combustible compounds (13). For monitoring measurements of work place exposure detection points should be selected at the height of breathing levels (5).

Although most equipment is designed for simple installation, care must be taken to follow the manufacturer's instructions concerning proper installation and coordination with other equipment. When sampling lines are used, these should be of a material that will neither contaminate nor degrade the sample being routed to the analyzer. Detection sensors and sampling probes should be protected from the weather, including extremes of temperatures (5). Installation of equipment should be located so that maintenance can be performed easily.

Alarm systems can vary greatly in complexity. A simple alarm system may provide visual and/or audible warning signals once a single or multiple preset concentration of vapor or gas is exceeded. Facility personnel can respond appropriately. Complex alarm systems may initiate automatic shutdown of the process or signal automatic mitigation efforts.

Maintenance should be conducted periodically according to the manufacturer's instructions. The system should be checked daily to ensure that the detector or sampling lines are not plugged. Calibration and adjustment of equipment should be performed periodically with vapor or gas standards of known concentrations. Proper operation and maintenance of the equipment requires proper training of facility personnel. This training may be included in the contract for the equipment, where plant personnel can learn the proper calibration and maintenance techniques from the supplier actually performing the maintenance during the equipment's warranty period (13).

4.4 APPLICABILITY AND PERFORMANCE

A variety of equipment is available to monitor flammable and/or toxic vapors from releases within plant environments and to use at remote chemical spill locations. As indicated in Subsection 4.2, these systems operate according to numerous detection principles. References 6 and 7 include detailed descriptions of available equipment. In these references, approximately 150 different direct-reading instruments and colorimetric indicators are described and the operating principles, performance data, and inferences are discussed. In addition, Reference 8 discusses several single-component and multicomponent vapor monitoring devices for monitoring hazardous releases from railroad accidents.

4.5 RELIABILITY

The reliability of detection and warning systems depends primarily on proper system maintenance and on visual and functional tests. For catalytic combustion detector elements, a 3 percent failure per month can be expected (14). For the portion of the instrument where adjustments for the span, zero, and alarm set points can be made, an 0.5 percent failure per month can be expected (14).

The reliability of detection systems may be affected by contaminants. Sulfur compounds may form acids that permanently damage the sensor catalyst, while halides can coat the sensor and cause a loss of sensitivity (14). For other types of detection systems, there may be chemical compounds that interfere with the accurate detection of the hazardous vapor being analyzed.

4.6 SECONDARY HAZARDS

Because of potential fire hazards, the use of detection and warning systems should follow all applicable electrical codes. Where necessary, systems should be approved for use in classified hazardous areas.

Personnel maintaining and checking release alarm situations should wear approved safety equipment to prevent exposure to hazardous concentrations of vapors and physical injuries.

An indirect secondary hazard of detection and warning systems is that they may engender complacency. These systems should not be substitutes for proper accidental release prevention measures.

4.7 COSTS

The costs of detection equipment vary widely, depending on whether the device is monitoring a single vapor or gas or several. Some typical estimated costs of different types of detection systems are presented in Table 4-3 (4,8,16).

TABLE 4-3. EXAMPLES OF ESTIMATED COSTS

Equipment	Capital Cost ($)
Manually operated portable sampling pump for colorimetric indicating tubes	135
Battery powered portable combustible gas analyzer	300 - 7,000
Multicomponent monitoring devices (gas chromatographs and infrared analyzers)	5,000 - 35,000
Remote area-wide detection systems (laser based, infrared, and ultraviolet systems)	15,000 - 175,000
Mobile mass spectrometer	500,000

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SECTION 5

VAPOR DISPERSION MODELING

Mathematical models that accurately simulate the movement of a hazardous vapor cloud from an accidental release are valuable for predicting the effect of various accidental release scenarios and, to a limited extent during an actual release event, for determining whether community evacuation is required. Models are available today that support both of these tasks. However, the usefulness of a model during an actual release event is often limited by a lack of information and by the time required to activate the modeling process. Vapor dispersion models should not be used as the only source of information for decision making during an actual release event, but they can help the emergency response expert choose the appropriate response for the specific situation.

This section of the manual discusses vapor dispersion models for predicting the impact of an accidental release. Types of models are discussed in terms of their applicability, performance capabilities, and reliability.

5.1 BACKGROUND

Mathematical vapor dispersion modeling to predict the potential impact of an accidental release is a relatively new field. Traditional vapor dispersion modeling has focused on the atmospheric dispersion of pollutants from an elevated stack. Such models deal with low concentrations of pollutants in air continuously emitted over a long period of time. Models for predicting the effects of an accidental release, however, must be able to handle short-term releases at both high and low concentrations and at variable release rates. They must be capable of modeling a release/dispersion of heavier-than-air and lighter-than-air materials, and materials that have the same density as air. Such models should simulate a variety of possible release forms, such as a release from a boiling pool of liquid, or a release from a hole in a pressurized vessel.

One purpose of a vapor dispersion model is to predict the area that might be adversely affected by the vapors from a release. The adverse effects will depend partly on the properties of the released chemical. For flammable materials, the presence of vapor concentrations within the flammable limits of the material are of concern because such concentrations can be ignited. For toxic materials, the presence of vapor concentrations greater than the compounds IDLH (immediately dangerous to life and health) will be of concern (1).

One modeling method used to predict vapor cloud movement is experimental physical modeling, such as in wind tunnels or water channels. In these experiments, a scale model is used to simulate the release, using air and the actual chemical of interest or liquid substitutes. Some success has been achieved using these methods (2,3,4); however, the rest of this section focuses on mathematical models because of their convenience and intense development in recent years.

Mathematical vapor dispersion models may be used for two purposes: to assess hazards and plan an emergency response, and to provide emergency response guidance information during an actual accidental release. Modeling may be used to predict the effects of various accidental release scenarios and to estimate which scenarios present the greatest threat to plant personnel and to the community. Modeling may be used to estimate what portions of the community might be affected during various accidental release scenarios. This information can be used to develop community emergency response plans. Models may also be used during an actual release event to help the emergency response coordinator make decisions about what action should be taken if a release occurs.

A distinction should be made at this point between individual dispersion models and what could be called emergency response modeling packages. Many of the models sold commercially would come under the category of emergency response modeling packages. Such a package will typically contain a set of source models, a dispersion model with a number of submodels to handle non-idealities, a database with chemical property data for a variety of potential release candidates, the ability to use real-time meteorological data if an actual release occurs, and a visual display that shows the physical motion of the cloud. Such packages are often customized for specific sites with a map of the area shown under the released vapor cloud. Some packages can be set up to communicate directly with detection and emergency response notification systems.

Some mention of "real-time" response models should be also be made. For a model to be "real time" it must react or change its simulation as actual events occur. In most accidental release situations, a model is activated some time after the release has begun (from minutes to hours). Information describing the actual event, necessary for model input, may also not be available for some time after the release has begun (if at all). A true "real-time" model would have to be monitoring sensors at possible event sites. When it appears that a release may be imminent, the calculations are activated. The necessary data would be obtained by the model itself. Such a system would be quite complex, and no such system is known to exist. The existing "real-time" response models usually only use real-time meteorological data in a predefined release scenario.

5.2 DESCRIPTIONS

Two key components of models must be available to fully describe an accidental chemical release: a source model component and a vapor dispersion model component.

5.2.1 Source Models

A source model is required to calculate the effect of the initial release conditions on vapor dispersion. For example, a release from a refrigerated storage vessel containing a liquefied gas will behave differently than a release of the same material from a pressurized, non-refrigerated storage vessel. The difference between these two releases is not a difference in the material released, but in its physical state. Source models must be used to calculate the effects of these differences. Examples of the types of information generated from a source model which becomes information that a dispersion model can use include the following: the rate of vapor generation, the height of the release, the initial velocity and temperature of the vapor, and the initial concentration of the released vapor.

Each type of release will require a different set of mathematical equations to define the nature of the release. The physical state of the released material and the way in which the loss of containment occurs will both affect the calculations required to define the release. Examples of possible physical states of released materials are:

- Release of a pressurized liquefied gas;
- Release of a chilled liquefied gas, stored at atmospheric pressure;
- Release of a pressurized gas;
- Release of a liquid stored at ambient or elevated temperature and pressure; and
- Release of a two-phase slurry.

Some examples of different ways a release may occur are:

- Release from a ruptured pipe;

- Release from a hole in a vessel;

- Release from an activated pressure relief device;

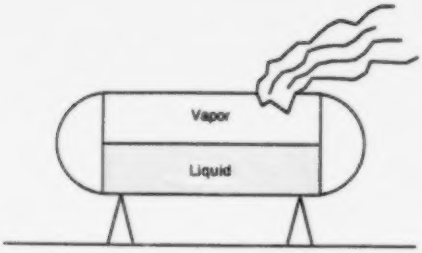
- Sudden release of the entire contents of a vessel;

- Opening a valve that results in a release from a non-blanked pipe; and

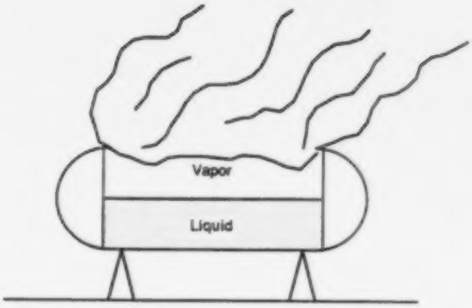
- Any of the above releases within a diked area, or any of the above released within an enclosure.

A wide variety of release scenarios can be modelled by combining the physical state of the released material with the conditions under which the release occurs. Figure 5-1 illustrates a few possible release situations. Ideally, a source model will be able to take these combinations and ambient weather conditions and determine whether a boiling pool of liquid is formed, whether the release is entirely gaseous, whether an aerosol is formed or if the release is some combination of each. This information is then used to define the initial conditions of the vapor from the release.

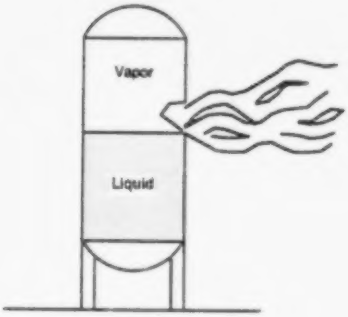
Source models can be obtained either as part of a model package that contains both source and dispersion models, or as separate packages. Table 5-1 gives the names of some source models, although this list is not exhaustive. Examples of modeling packages that contain both source and dispersion models are presented in Subsection 5.2.2 on dispersion models. Additional information about these models will be discussed in Subsections 5.3 and 5.4.


Vapor
Liquid

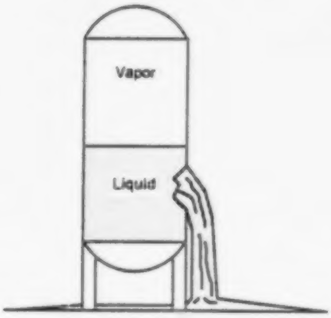
SMALL HOLE IN THE VAPOR
SPACE OF A PRESSURIZED TANK


Vapor
Liquid

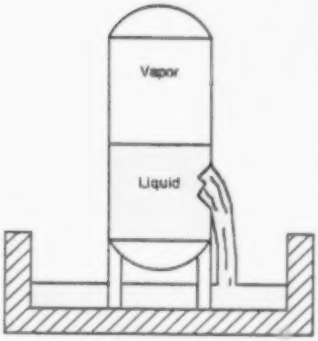
CATASTROPHIC FAILURE OF
A PRESSURIZED TANK


Vapor
Liquid

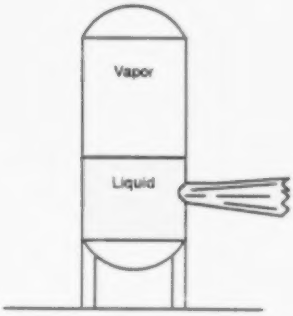
TWO - PHASE RELEASE
FROM A PRESSURIZED TANK


Vapor
Liquid

SPREADING POOL OF
REFRIGERATED LIQUID


Vapor
Liquid

SPILL OF REFRIGERATED
LIQUID INTO DIKED AREA


Vapor
Liquid

HIGH VELOCITY JET OF
REFRIGERATED LIQUID

Figure 5-1. Potential release scenarios.

TABLE 5-1. EXAMPLES OF SOURCE MODELS

Authors	Sponsor	Application
Tang et al (1980)	U.S. Coast Guard	Oleum/H_2SO_4 spills on water
Clewell (1983)	U.S. Air Force (ESL)	Parameters presented for approximately 25 chemicals
Shen (1982)	New York State Dept. of Env. Conservation	Volatilization from exposed water surface
Whittaker (1977)	Alberta Environment	H_2S risk assessment modeling
Kahler et al (1978)	U.S. Air Force	Specific to N_2O_4 (pool evaporation)
Whitacre and Myriski (1982)	U.S. Army	Toxic liquid spill (pool evaporation)
Ille and Springer (1978)	U.S. Air Force	Dispersion modeling of propellant spills (pool evaporation)
Wu and Schroy (1979)	Monsanto Company	Pool evaporation, chemical spills
Reid and Wang (1978)	American Gas Association	LNG spills in different substrates
Shan and Brisiac (1978)	U.K. Safety and Reliability directorate	LNG applications with suggestions other liquids
Reid and Smith (1978)	California Public Utilities Commission	Estimates of LNG release rates for subsurface spills
Georgakis et al (1979)	Distrigas Corp.	LNG and Gasoline

Source: Reference 5

5.2.2 Dispersion Models

Of the two extreme approaches for modeling vapor dispersion, attempts to solve the problem exactly by using differential equations that describe each process affecting the motion and dispersion of the vapor in air. The equations are integrated with time over three-dimensional space. This type of model is called a three-dimensional numerical model.

The second extreme is one that makes simplifying assumptions for each differential term used in the three-dimensional numerical model until the equations can be combined and simplified to form a single equation.

A large number of models can be formed with characteristics of both these extremes. By making a limited set of simplifying assumptions, models can be created whose solutions cover a specific range of accidental release cases. In this manual, such models are called similarity models.

Similarity models --

Similarity models avoid the complexity of specifying the details of how the physical properties of the cloud vary from point to point and, instead, are written in terms of the bulk or integrated properties of the cloud. Instead of calculating how the velocity, concentration, and other characteristics change along a stream line, they determine how these bulk properties change as the cloud moves downwind. These models generally assume that the material behaves as a massless quantity that in no way influences the turbulent atmosphere in which it disperses. One of the best known examples of this type of model is the gaussian plume model.

When the cloud formation time is very small compared with the time of cloud travel, the cloud may be approximated by the formation of an instantaneous cloud or "puff", as it is typically referred to. If the release is continuous, some similarity models will approximate the release by modeling a series of instantaneous "puffs." The concentration at any point may be determined by summing the contributions at the point from each of the puffs.

By making the assumption of continuous source strength and a constant wind speed and direction, this summing can lead to a single expression describing the concentration anywhere in the plume. This expression is known as the continuous Gaussian plume model. By using puffs, noncontinuous time-dependent source strengths and meteorology can be simulated (5,6).

In practice, similarity models often solve differential equations with simplifying assumptions. For example, a similarity model may account for the change in the volume of a puff caused by entrainment by using differential equations of motion and entrainment, but make the simplifying assumption that the concentration in the puff is Gaussian in nature.

A wide number of similarity models are available both publicly and from commercial sources. The differences, or lack of difference, between these models was summarized by one author as follows (7);

> The current generation of public domain and commercially available source or dispersion models is not notably innovative in formulation. This is a result of the current state of the science of dispersion meteorology. Differences among models do not represent innovation, but are related to the selection and combination of different theoretical expressions for efficient programming or the use of different frameworks for data handling and presentation.

Table 5-2 presents examples of similarity dispersion models. Table 5-3 presents examples of modeling packages that contain source and similarity dispersion models. Table 5-4 shows examples of commercial modeling packages that use similarity dispersion models. These lists are not exhaustive. Additional information is presented in Subsections 5.3 and 5.4.

Three-dimensional numerical models --

In three-dimensional models, the distributions of velocity and concentration are determined by the solutions of the conservation equations of fluid flow and the prescribed boundary conditions. These models take a much more

TABLE 5-2. DISPERSION MODELS

Model Name	Sponsoring Organization
British Gas	Cremer and Warner
(Chlorine Institute)	Chlorine Institute (CI)
DENZ	U.K. Safety & Reliability Directorate (SRD)
DEGADIS	Dense Gas Dispersion Model U.S. Coast Guard
INPUFF	EPA Integrated Puff Model
(IEPA)	Illinois EPA
HEGADIS-II	Heavy Gas Dispersion from Area Sources Koninklijke/ Shell Lab
OB/DG	Ocean Breeze/Dry Gulch (U.S.A.F.)
EIDSVIK	Norwegian Institute for Air Research
SLUMPING	Royal Netherland Meteorological Institute
SLAB	Lawrence Livermore National (LLNL)
SRI PUFF	SRI International
WINDS	Savannah River Lab (SRL)

Source: Reference 5

TABLE 5-3. SOURCE AND DISPERSION MODEL PACKAGES

Model Name	Sponsoring Organization
AGA (LNG)	American Gas Association (AGA)
AGA	Germeles & Drake
DDESB	Department of Defense Explosives Safety Board (DDESB)
ICARIS	Industrial Chemical Accident Response Information System of the Association of American Railroads
HACS	Hazard Assessment Computer System U.S. Coast Guard
FUMING ACID	Proctor & Gamble
(Standard Oil Co.)	Standard Oil Co. (Indiana)
TOXCOP	Toxic Corridor Prediction U.S. Army Atmospheric Sciences Lab (ASL)
SPILLS	Shell Development Co.

Source: Reference 5

TABLE 5-4. COMMERCIAL MODELING PACKAGES

Model Name	Sponsoring Organization
Dispersion Models	
DAISY	Dispersion Analysis Information System, Dow Chemical
TRPUF	Trinity Consultants
Source and Dispersion Model Packages	
CEES/ERADAS	Energy Impact Associates
CHARM	Complex Hazardous Air Release Model Radian Corporation
COBRA	Concord Scientific Corporation Dames & Moore
CARE	Environmental Systems Corporation (ESC)
AIRTOX/HASTE	Environmental Research and Technology (ERT)
ETA	ETA, Incorporated
MIDAS	Pickard, Lowe, and Garrick, Inc.
MESOCHEM	IMPELL Corporation
SAFER	Safer Emergency Systems

Source: Reference 5

rigorous and theoretical approach to the diffusion problem than do similarity models. A primary use of these models is to predict the dispersion of a vapor cloud around obstructions and irregular terrain.

Several three-dimensional numerical models have been developed for use on toxic releases. All are experimental at this point. Additional information may be found elsewhere (6,8).

5.3 APPLICABILITY AND PERFORMANCE

The models presented in Tables 5-1 thru 5-4 are not all representative of the state of the art; some have been superseded by further developments. Also, some of these models were developed for very narrow applications and will be of limited use for general accidental release modeling. Some models were developed for a purpose that did not require the accuracy necessary for modeling accidental releases of toxic materials. These models incorporate simplifications that are not appropriate for accidental release modeling. The potential users must determine their requirements and select a model accordingly. One source has summarized the important questions in model selection as follows (7);

- What is the time frame in which results are required?
- Who is the intended user?
- What is the source configuration and what are likely accident scenarios?
- What are the chemical and physical characteristics of the material released?
- Does local terrain influence dispersive patterns and what is the local dispersion climate?

The present generation of models is most valuable as an emergency response planning tool. Models should not be used as the sole decision-making tool during an accidental release, and with the current limitations of "real-time" modeling they may be of little use during an actual event. Instead, model results should be used to help the emergency response expert during an accidental release situation.

Ideally, before a release occurs, single page reports containing response information for likely releases would be created by using a model. These single pages could then be used by nontechnical persons in an actual event until more information was available for a refined estimate of impact.

Only those models that use an empirical or simplified approach to model vapor dispersion (similarity models) are useful in the emergency response model because of the calculation time involved. These simplifications restrict the accuracy of the models. However, these same simplifications allow the models to fairly rapidly produce a result accurate enough for the purposes mentioned above. At this time, models that take a more rigorous approach (three-dimensional models) cannot produce rapid results. Also, these models require large quantities of data to achieve accurate results and such data may not be available.

Several potentially desirable modeling features are either not available, or are not fully developed at this time. Some of these features are discussed below:

- The effects of post-release mitigation measures such as foams applied to the spill surface, or water sprays;
- Adequate complex terrain models;
- Modeling of atmospheric turbulence;

- Models for certain types of sources, such as high-pressure jets, or two phase releases;

- The ability to model multi-component releases;

- Accounting for chemical reactions, such as the effect of atmospheric moisture on water reactive releases; and

- The effect of fire on the release and the dispersion of the resulting fire decomposition products.

5.3.1 Source Models

Most source models used in conjunction with air models are designed to calculate the evaporation rate from pools of spilled liquid. These models calculate an evaporation rate based on mass and heat transfer equations. All evaporation source models apply some simplifying assumptions. Some models assume that the pool forms instantaneously and is of a fixed radius defined by the model user. Other models calculate the size of the pool as a function of time. Most models have restrictions on the range of materials that can be modeled. Additional simplifications made by most vaporization models include (5);

- Models are for single component systems;

- Ice formation in the soil is not considered;

- Percolation into the soil is specified (as opposed to calculated), or not considered; and

- Runoff from the spill area is specified or not considered.

For models that calculate the size of a spill pool, calculation of the rate of spilled material into the pool is based on user-defined spill parameters. Most often these parameters are the size and location of a hole in a vessel. The models will typically use an orifice flow equation to calculate the flow into the pool. Source models that handle vapor releases will also use some type of orifice flow equation to calculate the rate of vapor release.

The modeling of more complicated sources has not been incorporated into vapor dispersion modeling. Examples of complicated sources would be the release of two-phased flow or the release from a high-pressure jet. There are two reasons why these types of flow have not been incorporated into atmospheric dispersion models. First, the behavior of such releases is not well understood and the mathematics of the sources have not been developed. Second, the complexity of these sources would make it difficult to get meaningful results when used with similarity models. A complex source would probably need to be used with the more complex three-dimensional models, and three-dimensional models themselves are not yet practical for modeling accidental releases.

Another issue of concern when considering source model reliability is the selection of an appropriate source model for a given situation. Each potential type of release will require a unique combination of calculation procedures to model the result of the release. The issue of source model selection is of particular concern when a release is being modeled as it occurs. In this event, the modeling package used must not only have a source model for the type of release that has actually occurred, but must be able to select that model and set all of the model parameters to be consistent with what has actually occurred. This shows one of the limitations of using dispersion models for modeling "real-time" events.

5.3.2 Dispersion Models

Similarity Models --

As was discussed above, similarity models use a simplified approach for solving the problem of the dispersion of gases from an accidental release. Even with these simplifications, similarity models offer the best available option for modeling such releases. The simplifying assumptions allow the models to operate rapidly enough on a computer to be used to predict the movement of a release even after the release has begun. All of the emergency response modeling packages sold commercially incorporate similarity models. As will be discussed below, modifications to these models have allowed some of them to handle some of the nonideal conditions encountered in real release situations.

A state-of-the-art similarity model, interfaced with a state-of-the-art source modeling package will produce accurate enough results to be used for the following purposes;

- By modeling a series of credible worst case releases, plant designers can determine whether the siting and layout of a potential plant is appropriate.

- Plant designers can also use these modeled events to evaluate what prevention, protection, or mitigation technologies might be appropriate at various locations within the plant.

- A series of credible worst-case releases can be modeled for an existing plant. Plant management and engineers can use the results to evaluate the same features mentioned above for a new plant. A heavier emphasis would be placed on prevention, protection, and mitigation than on siting and layout. The effect of some of these control measures could be tested using the model. For example, many models allow the effect of diking to be tested.

- An emergency response system that incorporates a modeling package could be set up to help the emergency response coordinator decide what actions would be appropriate in the event of an accidental release.

As has been discussed, similarity models are not accurate enough to serve as the sole basis for decision making during an actual accidental release event.

The assumptions and simplifications incorporated into similarity models impose basic restrictions on prediction accuracy. Individual models will incorporate varying degrees of complexity and varying degrees of accuracy. However, certain simplifying assumptions will be common among most similarity models. One source has summarized these assumptions as follows (5);

- Meteorological conditions are assumed to be constant during the simulation period, which is typically one hour. The effects of any systematic change or trend in wind speed, wind direction, or stability conditions during an hour would not be described by the model.

- Winds and turbulence are assumed to be the same at all locations throughout the boundary layer. The effects of wind speed, or wind direction shear, or of changes in turbulence with height are not considered within the Gaussian formulation.

- The basic model averaging time is assumed to be long, compared with the time scale of turbulent atmospheric motion and with the transport time from source to receptor.

- Pollutant mass is conserved within the Gaussian formulation. Processes that add or remove mass, such as deposition, decay, or chemical transformations, are assumed to be of secondary importance.

Many models have incorporated modifications in an attempt to improve the performance for non-ideal situations. Some incorporate mathematical expressions to account for the movement of gases that are heavier than air (many toxic materials fall into this category) (5,9,10). Methods have been developed to account for simple wind shear and for occasional changes in wind speed and direction (5). Some work has been done to allow for the deposition of materials from the vapor cloud, or for the time-dependent decay of the material. A few similarity models have incorporated methods for simulating the effect of certain types of complex terrain. All of these modifications are made using simplified approaches to complex phenomena. However, most of these phenomena have not been modeled using more rigorous approaches, and for the present time, the simplified approaches offer the only practical solution.

Naturally, the accuracy of predictions made by a similarity model will depend somewhat on the accuracy of the source model used. As a result, predictions made using an adequate source model can be misleading. Additionally, the way the source model interacts with the dispersion model may affect the overall accuracy.

Three-Dimensional Models --

Three-dimensional models can, in principle, simulate the dispersion of vapors as a function of space and time without the simplifications incorporated into the similarity models. These models should be able to account for the effects of terrain and wake turbulence. Although they appear to be theoretically correct, several factors limit their usefulness at this time.

First, the model theories and assumptions have been developed from an inadequate experimental data base. A variety of methods have been developed for handling the effects of turbulence on diffusion, yet the accuracy of the assumptions in each case are difficult to evaluate because of the present lack of experimental data (6).

Second, these models require large quantities of data, large computer storage and computational capacity, and long calculation times, features that make it difficult to run multiple comparative runs for planning purposes, and that make their use during actual release events impractical.

Finally, most of these models have yet to develop computational routines that give highly accurate results. For example, most of these models compute diffusion by dividing the physical vapor cloud and time into many pieces or elements and performing momentum, mass, and energy balances around each element. An error will be introduced into the calculation that is inversely proportional to the number of elements that the cloud is divided into and the size of the time increments chosen. An infinite number of elements will result in no error, while dividing the cloud into one element will result in a very large error. Also, there are rounding errors produced by carrying a finite number of significant figures in each calculation. These errors accumulate and can become quite significant. The size of the accumulated error will be inversely proportional to the amount of computer computation time required. This compounds the problem mentioned in the previous paragraph.

Because of their potential accuracy and ability to model complex situations, three-dimensional models may eventually replace similarity models as the preferred method for modeling accidental releases; however, the areas of dispersion theory, numerical methods, and computer technology need improvements before this will occur.

5.4 RELIABILITY

One way to measure model reliability is to compare actual test data with model prediction. A limited number of such tests have been performed, and comparisons of the data with several models have been published. A major comparison of models was done for the Chemical Manufacturers Association (5).

The list of models mentioned in the report is quite large, but actual data comparisons were only performed for nine of the models. The material released was Freon.

The U.S. Air Force has compared other models with field data. The results are shown in References 11 and 12. Comparisons were for nitrogen tetroxide spills and an inert tracer. In 1986, Amoco Chemical Company performed a series of full-scale hydrogen fluoride releases at the Department of Energy's spill test center in Nevada. Liquid hydrogen fluoride, stored under pressure and at ambient temperature, was released to determine if such a release could be modeled accurately by existing source and dispersion models. Test results were presented in late 1987 (13).

There are plans to continue test releases of toxic substances to gather data for model comparison/development. For the most part, these tests are carried out at the Department of Energy's Nevada Test Site.

5.5 COSTS

Models in the public domain are available for a copying fee that may range up to several hundred dollars. The main expense associated with most of the public domain models is the time the user needs to become familiar with the model and adapt it to specific requirements. Most of the models in the public domain have limited applicability; therefore, several models may be required to meet all the needs of the user.

Most of the commercial modeling packages are assembled so that comparatively little time is needed to become familiar with the model. Also, many companies that market the commercial modeling packages will customize the model for the specific needs of the user. Several man-months may be required for such an effort. Such features are reflected in the higher cost of commercial modeling packages.

Commercial modeling packages may be divided into two cost groups. The first is composed of modeling packages that sell for less than $50,000 (includes hardware and software). At the bottom end of the cost range is one company that has packaged the EPA puff model (with no heavy gas dispersion capability) for use on a personal computer. At the top end of this cost range are packages that include multiple source models, data bases with the physical and chemical properties of many different chemicals, and a meteorological tower that sends data to the system to be used during an actual accidental release. These higher-priced packages incorporate a degree of flexibility so that the user can adapt the package for specific needs or use the model for a number of different release situations.

The second group of commercial modeling packages are those that sell for over $100,000 (including hardware and software). These systems have the capabilities of the higher-priced models from the first group, while adding extensive customization for the specific location where they will be applied. The packages can also include a number of features that aid the emergency response effort but that are not part of the modeling system. Such features may include recorded phone messages that are automatically sent to local fire and police in the event of an emergency.

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SECTION 6

METEOROLOGICAL INSTRUMENTATION

Meteorological data can serve several roles in the mitigation of accidental releases. First, historical data can be used to run vapor/gas dispersion studies for planning emergency response procedures. Second, real-time meteorological data are essential for choosing correct mitigation and emergency response actions at the time of an actual release.

This section presents guidelines for gathering and using meteorological data. General specifications for instrumentation are recommended, and basic considerations for the siting of meteorological systems are discussed.

The information presented in this section is general in nature; meteorological data needs and the design of meteorological systems for specific applications must be assessed case by case.

6.1 BACKGROUND

When applied to facility design and emergency response planning, meteorological data are useful for selecting mitigation measures for accidental releases. When an actual release occurs, these data can facilitate emergency response by real-time estimation of toxic cloud transport and of the potential effects on sensitive receptors. Meteorological data can also be used to analyze past events and to predict the consequences of various accidental release scenarios of possible future events. The following subsections discuss the utility of historical and real-time meteorological data to a facility or the surrounding community for accidental release applications.

6.1.1 Historical Data

Historical meteorological data can be used in facility design, emergency response planning, and the historical analyses of hazardous releases.

Facility Design--

Meteorological data can play a major role in the design of a facility to protect sensitive receptors from the effects of accidental releases. The facility designer can obtain one or more years of representative wind direction data to determine the frequency distribution of wind direction and speed in the vicinity of the facility. With this information, the facility designer can locate potential toxic release points to minimize the probability of their being upwind of sensitive receptors.

Using a more rigorous approach, the facility designer can use hazardous release dispersion models (see the dispersion modeling section of this manual) to determine the optimal locations for potential toxic release points. The model user is allowed to select various meteorological and release scenarios. As noted in the dispersion model section of this manual, wind speed, wind direction, air temperature, humidity, and atmospheric stability class are parameters commonly used by these models. The criticality of the various meteorological parameters depends on the specific chemical and other characteristics of the source during a release.

Examples of the use of meteorological data for facility design purposes have been provided by Boykin and Kazarians (1).

Emergency Response Planning--

Historical meteorological data can be used to help determine where the significant effects of toxic releases would most likely be felt; this information can be used to help assess the degree and type of emergency response planning necessary. Historical meteorological data should be used for emergency response planning during the facility design stage because careful consideration of meteorological data at this point can reduce the emergency response planning effort if potential toxic release points are located. In the case of an existing facility, meteorological data can still be used to help determine the potential effects on sensitive receptors, which makes possible an assessment of the type and degree of emergency response planning needed. The methodology for using meteorological data for emergency response planning is similar to that described in the previous subsection for facility design.

Historical Analysis of Accidental Releases--

After an actual release, meteorological data from the release period can be combined with other data and observations of the actual release to better understand what has occurred. Meteorological data used for this purpose can provide comparative information on observed effects versus predicted effects. This information may be useful for mitigating future hazardous releases. For example, the placement of potential toxic release points in future facility designs or emergency response planning might be influenced by the analysis of an actual release.

A simplified approach to using meteorological data for historical analysis involves using wind direction and wind speed data for arriving at a crude estimate of the transport path of the released cloud. A more in-depth analysis would use hazardous release dispersion models for predicting the path of transport and the specific effects on selected receptors along the transport path.

On-Site versus Off-Site Historical Data--

Historical data used for the purposes described in the previous subsections should be obtained from on-site instrumentation if the meteorological instruments are sited properly (see Subsection 6.3.4, Siting of Meteorological Instrumentation). In many cases, however, historical data gathered on site may not be available or may be insufficient. In such cases, off-site data may have to suffice. If off-site data are used, the adequacy of the data must be carefully assessed. Off-site meteorological data collected near the plant would be more representative of conditions at the plant than off-site data collected far from the plant. Data obtained from a distant source or from an area with significantly different topography may not be useful.

6.1.2 Real-Time Meteorological Data

Real-time meteorological data at the time a release is occurring can be used by the emergency response team in appropriate models to predict the concentration levels and areas affected by a cloud or plume, thus enabling the response team to make more effective decisions about mitigation action.

The ability of the emergency response team to use real time data and a dispersion model depends on the conditions of the emergency (e.g., available reaction time, character of the release). In some cases, the usefulness of the model may be limited to a subsequent analysis of the event, as described in the previous section.

6.2 DESCRIPTION

This section describes the meteorological equipment that may be used for accidental release applications. Stability measurement techniques (inferred from measurement of other variables) and meteorological towers and data acquisition systems are also included. Much of the discussion of meteorological instrumentation is extracted from guidelines previously published by the U.S. EPA (2).

The intended use for the data determines which meteorological parameters should be monitored. When no dispersion model will be used, wind direction and wind speed data may be sufficient. When a dispersion model is used, additional variables such as temperature and humidity will probably be necessary. The variables needed depend on the model used (see Section 5).

Relative humidity and barometric pressure data are used in some hazardous release dispersion models; however, the sensitivity of the models to variations in these two parameters is minimal, and climatological averages can often be used. Thus, it is generally not necessary to obtain actual measurements of these parameters.

6.2.1 Wind Direction

Wind direction must be known in order to determine which direction the vapors from an accidental release will travel. Wind direction is measured with a wind vane connected to the necessary electronic circuitry to provide a remote readout and to record, if necessary, wind direction. Though rarely used for remote sensing, an elevated wind sock should also be used as a visual indicator of wind speed and direction. An elevated wind sock allows plant personnel to get an instant visual indication of wind direction from many locations at the facility, and it can also be seen off site, depending on its placement.

6.2.2 Wind Speed

Wind speed determines how quickly the plume or cloud from an accidental release will reach off-site receptors. A number of wind speed measurement systems that operate on different principles are available. The most commonly used sensors are the rotational cup and propeller anemometers. Cup anemometers operate on the principle that net torque (lift greater than drag) causes a rate of rotation roughly proportional to wind speed. The three conical cup design performs best. With propeller anemometers, the propeller turns at a rate almost directly proportional to the wind component parallel to its axis. Electronic circuitry converts the rotary motion of the cups or propeller to an electrical signal for remote readout equipment.

6.2.3 Ambient Temperature

Ambient temperature data are used in dispersion modeling to calculate cloud buoyancy and the heat available for evaporating volatile liquids. The most appropriate temperature measurement devices for meteorological applications are linear thermistors and resistance temperature detectors.

Thermistors are electronic semiconductors made from metallic oxides. The resistance of a thermistor varies inversely with absolute temperature. The system configuration is typically designed with the thermistor connected to a bridge circuit that provides an output voltage that varies directly with the temperature of the thermistor.

Resistance temperature detectors (RTDs) operate on the principle that the electrical resistance of a pure metal increases with temperature. An RTD operates connected to a bridge circuit that provides an output voltage that varies directly with the temperature of the RTD.

6.2.4 Stability

When accidental release dispersion modeling is conducted, data for atmospheric stability are essential for estimating the spread of the plume. Stability data are derived indirectly from measurements of other parameters. There are several methods for computing atmospheric stability. For example, one method calculates stability by evaluating the cloud cover, ceiling height and wind speed (Turner's 1964 method). Another method uses the standard deviation of the vertical wind direction; one uses the standard deviation of the horizontal wind direction; another uses vertical temperature differences. These methods are discussed extensively in the literature and in U.S. EPA guidelines (3).

The method used for calculating stability will depend on the method used in the specific vapor dispersion model. Some models allow a choice of methods.

6.2.5 Meteorological Towers

Several types of meteorological towers are commercially available for mounting wind and temperature instrumentation. Free-standing, guyed towers, as well as towers that can be attached to fixed structures, are available from a number of vendors. In some cases, meteorological instruments can be mounted on an existing elevated structure. Lightning protection kits, available from tower vendors, are recommended for areas where cloud-to-ground lightning is common.

6.2.6 Data Acquisition Systems

The most practical type of data acquisition system for the meteorological applications discussed in this manual is a digital system that uses magnetic media such as diskettes, cassettes, bubble memory, and semiconductor memory. Such systems allow immediate retrieval of data during actual emergency situations and provide the convenience of data retrieval and processing at any time. Many types of digital data acquisition systems with a wide range of memory capability are commercially available. System needs will have to be determined case by case.

6.3 APPLICABILITY AND PERFORMANCE

The utility of on-site meteorological data for hazardous release applications depends on the careful design of the meteorological data acquisition systems. Important considerations, discussed in the following sections, are variable selection, instrumentation selection, and instrumentation siting.

6.3.1 Instrument Selection

A number of wind vane manufacturers offer wind sensors with a rated accuracy of ±3 degrees, which meets EPA recommendations for prevention of significant deterioration (PSD) monitoring in standard air pollution applications (4), and which should be adequate for hazardous release applications. As with all meteorological sensors, the accuracy is actually the accuracy of the entire measurement system, including the readout device. Additional information on important wind vane performance criteria may be found in References 5, 6, and 7.

A wind sock is often used as a visual indication of wind direction. Although wind socks are rarely used for remotely sensing wind direction, they are extremely valuable to facility personnel as quick visual indicators. They should be used wherever an accidental release could present a hazard to facility personnel or to the surrounding community.

Many manufacturers offer wind speed sensors with a rated accuracy of ±0.82 feet per second or better, which meets EPA guidelines. As in the case of wind direction, the accuracy guidelines apply to the entire measurement system. Additional information on wind speed performance criteria may be found in Reference 8.

A wind sock may be used as a visual guide for estimating wind speed. Most manufacturers offer guidelines as to how the deflection of the wind sock correlates with wind speed. As mentioned in the previous discussion, wind socks should be used wherever an accidental release could present a hazard to the facility personnel or the surrounding community. Even when more sophisticated instruments are available, the wind sock should be used as a backup visual indicator.

Temperature sensor accuracies of 0.9°F or better are easily achievable (9). A number of manufacturers offer sensors with much better accuracy, although an accuracy of 0.9°F should be adequate for most accidental release applications (an exception is the case in which delta temperature measurements are needed for stability calculations; in this case, an accuracy of 0.18°F or better would be appropriate). It is important to note that temperature sensor accuracy is often limited by poor sensor exposure, improper coupling, and signal interference, rather than by the accuracy of the sensor itself. A serious problem in temperature measurements is radiation error, which can amount to several degrees at midday. Aspirated temperature radiation shields, readily available from manufacturers, can minimize radiation error.

6.3.2 Siting of Meteorological Instrumentation

The objective of proper meteorological instrumentation siting is to place the instruments at locations where measured data represent the atmospheric conditions in the area of interest. Proper instrumentation siting is of special importance for accidental release applications, since the data may be used for making critical decisions that affect human lives and property.

This section discusses instrumentation siting criteria, including the number and location of measurement sites, distances from obstructions, measurement heights and topographical considerations. The discussion focuses on the variables of wind direction, wind speed, and ambient temperature. Siting considerations for wind direction and speed receive the greatest attention, since data for these parameters are most sensitive to siting factors.

It is often difficult to locate a site that meets all the desired siting criteria. In any instance, site accessibility and security should never be overriding considerations; the integrity of the data may be significantly compromised if factors such as obstructions and topography are given too low a priority.

Siting for Wind Direction and Speed--

For accidental release applications, it is of utmost importance that reliable wind data be measured, since wind data (including stability calculated from wind data) determine the path and spread of the toxic cloud. The reliability of the wind data depends on the appropriateness of wind sensor siting.

Usually, the more wind data sites available, the more reliable the modeled estimates of accidental release transport. Some vapor dispersion models take advantage of multiple sites by weighting wind values according to the locations of the wind sites relative to the position of the plume at a given time.

The number and location of wind data measurement sites should be based on consideration of probable paths of cloud transport, the demographics of the facility vicinity, and expected variations in wind speed and direction caused by obstructions and non-uniform topography.

Using historical wind frequency distributions, the meteorological network designer should determine the relative probability that populations or properties in various directions from the facility will be located in the path of a hazardous cloud release so that the possible number of wind data sites and their locations can be determined. Wind data sites should be located as close as possible to the facility property boundary line, since data from a property line location should provide the best estimate of cloud transport into adjacent areas once the cloud has cleared the obstructions created by facility structures.

Once the number and general locations of meteorological sites have been determined, the network designer must analyze obstructions and topography to find specific sites that will produce data representative of areas potentially affected by a hazardous release.

It is standard meteorological practice to locate wind direction and wind speed sensors where the distance between the instruments and any obstruction is at least ten times the height of the obstruction (2). Examples of common obstructions are industrial facility structures, buildings, and large trees. Sites that are too close to obstructions will normally record wind speeds that are too low, wind directions that are unrepresentative of the area, and wind direction fluctuations that are too great (as indicated by the standard deviation of the wind direction).

While the adverse effects of obstructions on wind instrumentation siting can be determined and avoided rather easily in many cases, it is a significant challenge, at least in complex terrain, to assess the effects of topography on wind flow and to locate wind sensors where measured data are truly representative of the areas of interest. The meteorological network designer should carefully review topographical maps and determine the potential of the local topography (hills, creek beds, valleys, canyons) to cause channeling and upslope and downslope flows. The network designer must then locate the wind instrumentation sites so that the measured data are representative of the areas that may be affected by a hazardous release. When there are no significant obstructions to the flow of wind and the topography is level, wind measurements at any one site in the facility area should provide representative wind data.

The standard height for surface wind measurements in scientific applications is 33 feet (2). An appropriate wind measurement height for accidental release applications, however, will depend on the expected height of potential releases. For example, in the case of a non-buoyant toxic cloud that may flow near the ground, a wind measurement height in the range of 7 to 17 feet may be more appropriate than one of 33 feet. If a toxic cloud could be released at an elevated point, wind measurements at that height would be appropriate, especially during night-time periods when wind directions can vary significantly with height. When a facility contains multiple potential toxic release points at various heights, selection of an optimal wind measurement height may be difficult. In such a case, a measurement height that reflects the average of the release heights may be used.

Siting for Ambient Temperature--

The calculations made by hazardous release dispersion models of the dispersion of the released cloud are based on the ambient temperature at the time of release, and they assume that the temperature remains constant along the path of transport. It is usually sufficient to measure the ambient temperature at one location in the site vicinity.

The standard ambient temperature measurement height is 3 to 7 feet (2). For accidental release applications, however, the measurement height should be adjusted to correspond with the height of potential toxic releases. Such a height adjustment is most important during nighttime periods when variations in temperature with height can be significant. In case there are multiple potential toxic release points located at various heights, it is most practical to select a single height that best represents the heights of the release points.

Ambient temperature sensors should be sited so that they are not unduly influenced by heat sources such as exhausts. Locations directly over concrete or asphalt should also be avoided (2).

6.4 RELIABILITY

Meteorological instrumentation can be highly reliable if proper preventive maintenance procedures, as prescribed by the manufacturers, are followed. However, because of the importance of meteorological measurements for accidental release applications, spare parts and sensors should always be readily available.

For a meteorological system to produce valid and useful data, a well-designed program of quality assurance/quality control must be implemented and maintained. A stringent quality assurance/quality control program is particularly important for accidental release applications, since decisions affecting human health and the environment will frequently be based on meteorological data.

Examples of quality control measures include calibration checks, preventive maintenance, and spot data checks by personnel directly involved in operating the instrumentation. Quality assurance activities include equipment audits and detailed screening of the data sets by parties who are independent of routine system operations. A comprehensive set of quality assurance/quality control procedures has been developed by the U.S. EPA (2). These procedures are appropriate for meteorological systems deployed for accidental release applications.

6.5 COSTS

The cost of equipment and accessories for a station measuring wind speed, wind direction, and temperature typically ranges from $10,000 to $20,000. A number of vendors offer a variety of equipment models and configurations.

Components that should be considered when projecting costs for meteorological systems include the sensors; translator modules, racks, and power supply; junction boxes; cabling; wind sensor mounting crossarms; surge and lightning protection; data acquisition system; telemetry devices; calibration equipment; spare parts; and equipment shelter.

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SECTION 7

SECONDARY CONTAINMENT

In the event of the accidental release of a volatile, toxic and/or flammable liquid, the spread of the liquid must be controlled to reduce the rate of evaporation and the resulting generation of a vapor cloud. Physical barriers provided by judicious siting of storage and process facilities can contain and thus reduce the effects of a hazardous release. However, such barriers often do not exist or do not provide sufficient containment. In such cases, other methods of secondary containment are needed. Stopping or reducing the flow of a released chemical at the source will also help contain an accidental release. Sometimes the flow of material can be stopped by closing a valve of stopping a pump. At other times stopping the flow of released material requires the application of a leak plugging procedure.

This section of the manual discusses several methods for plugging leaks and stopping the flow of material upstream of a leak. A similar discussion and evaluation of several secondary or partial containment systems is also included. A brief discussion of costs is presented.

7.1 BACKGROUND

Post-release mitigation measures attempt to reduce the effects of an accidental release. The most effective method for reducing the effect of a release is to stop the release before large quantities of material have escaped. Using strategically placed, remotely operated emergency isolation valves is the most effective way of stopping the flow of material from an accidental release; however, in some cases, it is not possible to use valves to isolate a leaking portion of a process. An example would be a release from a hole in a large vessel. Such a release would continue even if the tank were isolated, as long as the liquid level was above the leak point or the internal pressure was sufficient to force vapors out. In such cases, leak plugging techniques might stop the flow of material.

Leak plugging specifically applied to accidental releases is not a common practice, although the Chlorine Institute has designed a number of leak-plugging devices for chlorine cylinders, one ton containers, and tank cars and tank trucks used to transport chlorine (1,2,3). In the chemical process industries, the desire to perform repairs without shutting down a process has led to the development of several plugging methods. Although these methods would have limited applicability to accidental release mitigation, the principles may be useful. The use of various chemical sealing materials for plugging chemical leaks has been investigated experimentally; none is in widespread commercial use. Such methods could be potentially applied to a number of accidental release situations. The following section discusses some of the leak plugging methods that may apply to mitigating releases.

In addition to efforts to stop the flow of the release at the source, the spread of any released liquid must be controlled. Limiting the spread of released liquids will limit the ground surface area affected by the release and will allow emergency response personnel to work close to the release source. In addition, containing the release will limit the surface area of the liquid, which will limit the rate of vapor generation, which can substantially reduce downwind vapor concentrations of volatile liquids. Finally, containment can be used to divert released liquids into a temporary containment vessel, thus substantially reducing the impact of the release.

Secondary containment systems in the form of curbing, trenches, basins and dikes have been successfully used for many years in the chemical industry. Many improvements have been made over the years. The following section discusses some of the secondary containment systems available at this time.

7.2 DESCRIPTION

7.2.1 Leak-Plugging Techniques

Leak-plugging techniques may be divided into three groups: chemical patches and plugs, physical patches and plugs, and methods for stopping the flow upstream of a leak. Examples of each of these categories are discussed below.

Chemical Patches and Plugs--

A chemical patch or plug is made by filling a hole or crack with a material that solidifies in place after application. No chemical patching system has been developed for widespread commercial use. The concept has been experimentally tested and requires further developmental work. Three categories of materials have been tested for this application (4). Urethane foams conform to an irregularly shaped hole and expand in place, resulting in a tight seal. Nonexpanding materials react in place to achieve crosslinked structures which are relatively resistant to chemical attack. Examples of crosslinked materials include: various epoxy systems, quick-curing silicone rubber, and catalyzed polysulfide rubbers. The third category of materials that have been tested are thermosetting nonexpanding plastics (5,6,7).

Several different methods for applying chemical plugs and patches have been tested. In one method, the patching material is forced into the leak and held in place until it sets and forms a plug (4). A second technique has been tested for improving the ability of nonexpanding materials to plug a hole. In this method, the chemical patching material is used in conjunction with a supporting or backing material such as nylon cloth (4). Another application technique uses an elastomer "balloon" or cloth sack attached to the end of a lance. The lance is inserted into the leak and the balloon or sack is filled with a plugging chemical, thereby plugging the leak (4,8,9). This type of device is illustrated in Figure 7-1. A variation of this last type of device is a cloth bag that is wrapped loosely around a leaking valve or fitting with

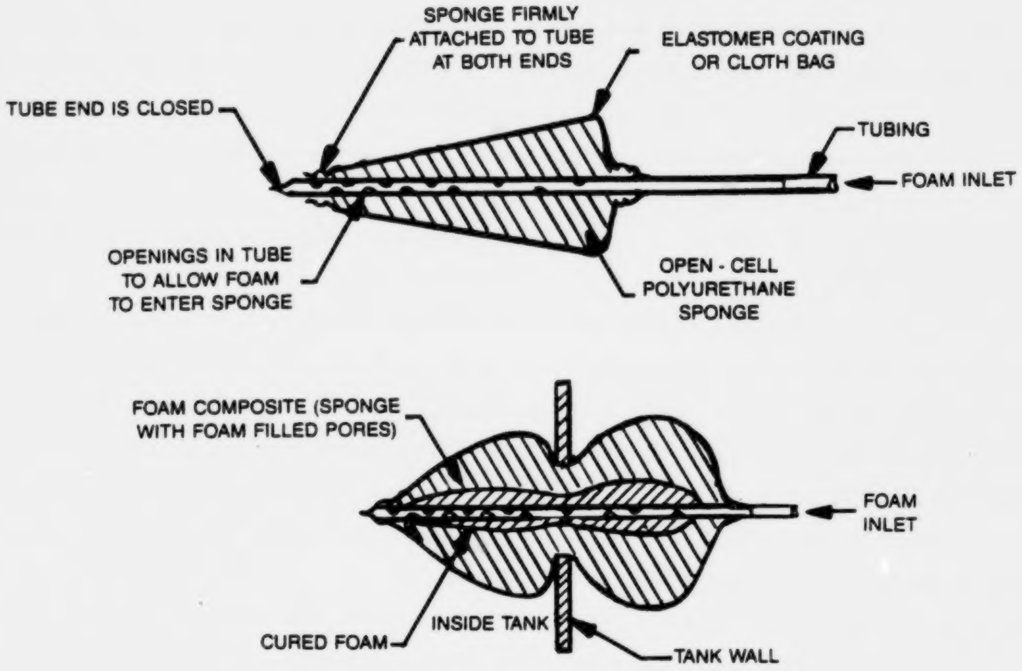

SPONGE FIRMLY ATTACHED TO TUBE AT BOTH ENDS
ELASTOMER COATING OR CLOTH BAG
TUBE END IS CLOSED
TUBING
FOAM INLET
OPENINGS IN TUBE TO ALLOW FOAM TO ENTER SPONGE
OPEN - CELL POLYURETHANE SPONGE
FOAM COMPOSITE (SPONGE WITH FOAM FILLED PORES)
FOAM INLET
CURED FOAM
INSIDE TANK
TANK WALL

Figure 7-1. Foam-injected leak plugging device.

Source: Adapted from Reference 10.

a leak-plugging chemical injected into the annular space between the cloth and the leak. The cloth holds the chemical in place around the leaking fitting until it can harden in place.

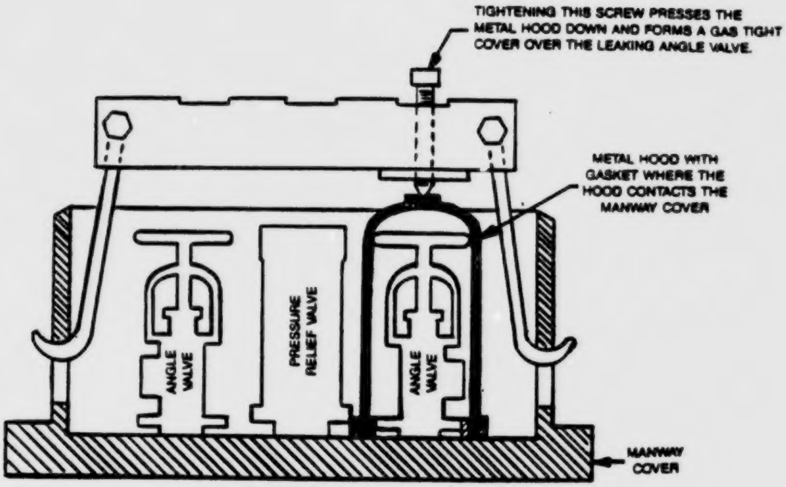
Physical Patches and Plugs--

A physical patch or plug is any prefabricated device used to fit into or around a leak; a multitude of such devices are available. The Chlorine Institute has assembled three emergency kits used to temporarily stop leaks from valves and fittings on cylinders, one-ton containers, and tank cars and tank trucks (1,2,3). Figure 7-2 illustrates some of these patching and plugging devices. The kits have patching devices for small punctures of cylinders and one-ton containers. This type of leak repair equipment is available from numerous other sources.

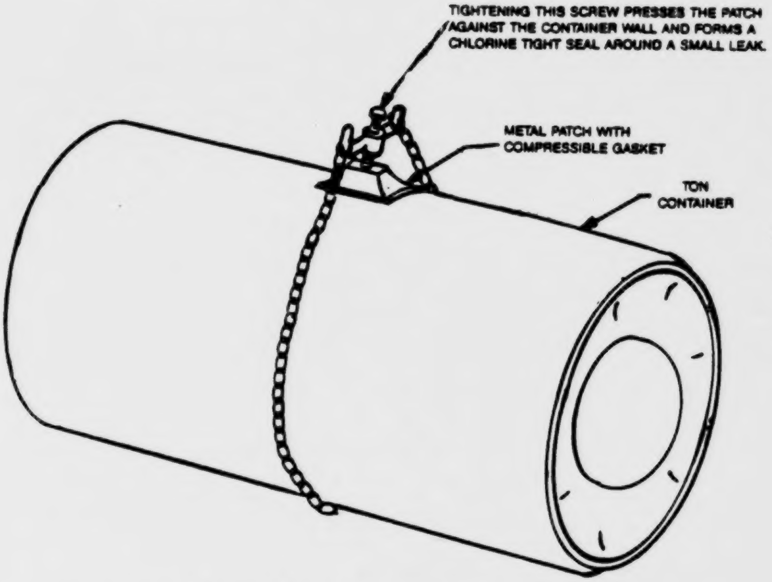
Several physical patching devices have been developed for leaking pipes, flanges or other fittings, so that pipe repairs can be made without shutting down the process. These devices, illustrated in Figure 7-3, are usually used to repair leaks of nontoxic materials such as steam, but they may be useful for preventing the release of toxic materials (6). This type of leak-plugging equipment is usually bolted or clamped around the leaking pipe or fitting, forming a leak-tight case. It is usually sized for a specific type of fitting or pipe. These devices are often used in conjunction with a chemical sealing material. For example, a metal jacket is bolted around a leaking pipe or fitting and a chemical sealing compound is injected into the annular space to more fully seal the leak (11). This type of arrangement is illustrated in Figure 7-4.

Methods for Stopping Flow Upstream of a Leak--

Analogous to leak-plugging methods are techniques developed for stopping the flow of material upstream from a leak. The most practical method for stopping flow would be shutting an emergency isolation valve. However, such valves are not always available. A few methods have been developed for stopping the flow of material in a pipe so that repairs can be made without


TIGHTENING THIS SCREW PRESSES THE METAL HOOD DOWN AND FORMS A GAS TIGHT COVER OVER THE LEAKING ANGLE VALVE.
METAL HOOD WITH GASKET WHERE THE HOOD CONTACTS THE MANWAY COVER
ANGLE VALVE
PRESSURE RELIEF VALVE
ANGLE VALVE
MANWAY COVER

Mechanical Leak Repair Device for Leaking Angle Valve on Manway Cover on Chlorine Tank Car


TIGHTENING THIS SCREW PRESSES THE PATCH AGAINST THE CONTAINER WALL AND FORMS A CHLORINE TIGHT SEAL AROUND A SMALL LEAK.
METAL PATCH WITH COMPRESSIBLE GASKET
TON CONTAINER

Mechanical Leak Repair Device for One Ton Chlorine Container With Small Side Wall Leak

Figure 7-2. Examples of mechanical leak repairing devices offered by the Chlorine Institute.

Source: Adapted from References 2 and 3.

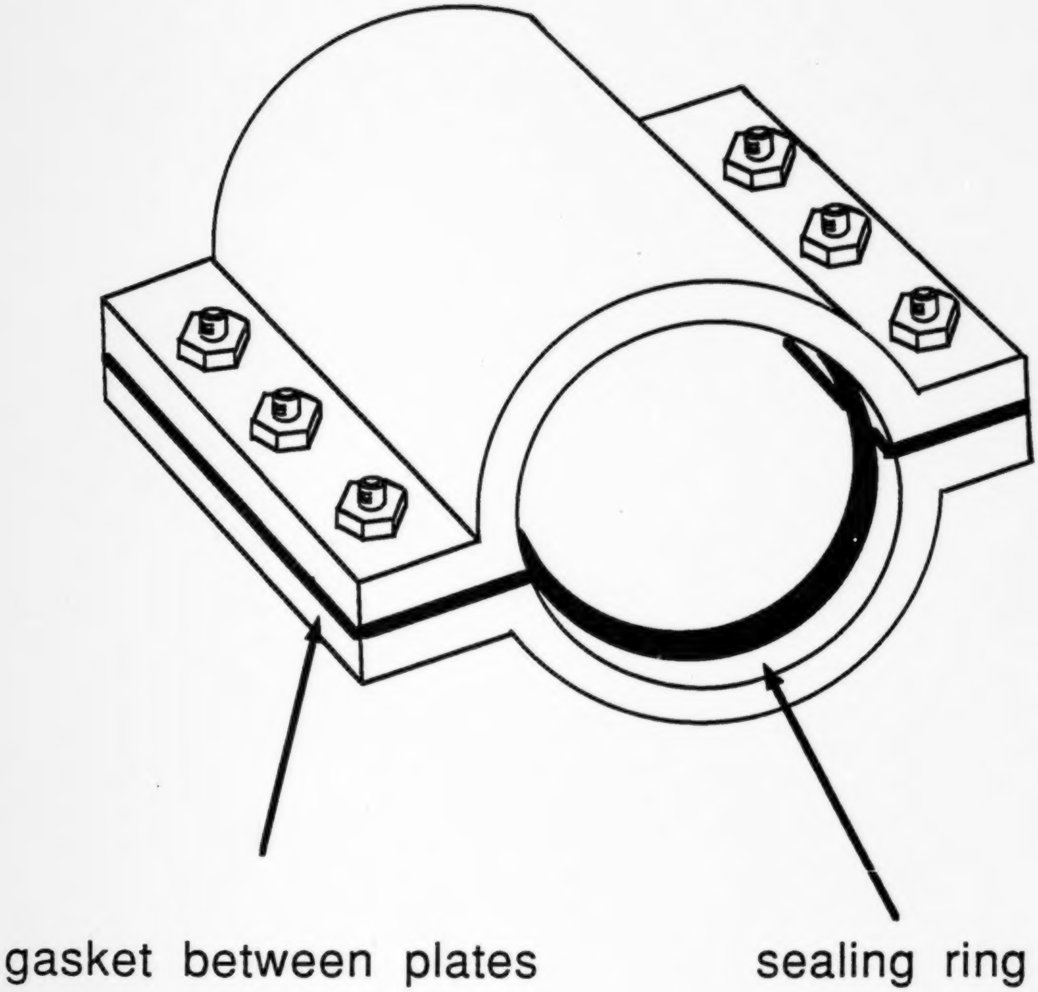

gasket between plates
sealing ring

Figure 7-3. Jacket that bolts around a leaking pipe, forming a leak-tight seal.

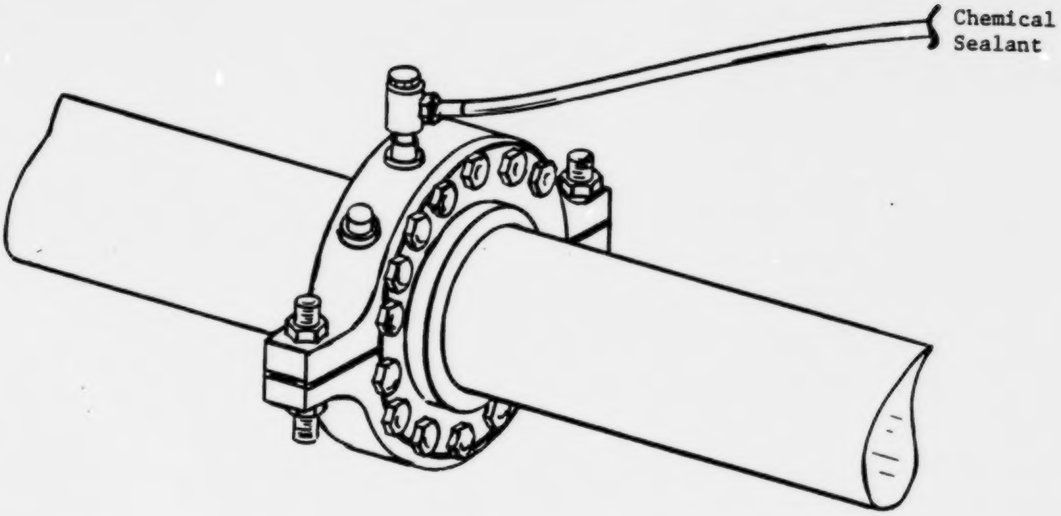

Chemical
Sealant

Figure 7-4. Mechanical sealing ring with injected chemical sealant to fit around and seal a leaking flange.

Source: Adapted from Reference 12.

shutting down a process. These techniques are probably not useful for most accidental release situations. However, they are discussed here to illustrate what the state of the art is at this time.

Pipe freezing, one method for stopping the flow in a pipe, has been developed primarily as a maintenance tool for making repairs in a pipe without shutting down an entire process unit (13). A temporary jacket is placed around the pipe where the freeze is to be made. The cooling liquid, such as liquid carbon dioxide or liquid nitrogen, is injected into the jacket and replenished until a solid, frozen plug is formed in the pipe. The plug is maintained by monitoring the temperature in the jacket and replenishing the coolant as required.

One company has developed a device for high-pressure steam applications capable of shearing a pipe and sealing the shear in place, thereby stopping the flow of material through the pipe (12). A similar method, called "stoppling," has been used for stopping flow in a line. In this technique, a reinforcing saddle is first welded or bolted around the line. A hole is drilled into the side of the line and a plug is inserted to stop flow in the line. The entire operation is kept under sufficient pressure to prevent any liquid in the pipe from escaping.

7.2.2 Physical Barriers and Containment Systems

Secondary containment systems typically consist of the following: curbing, trenches, excavated basins, natural basins, and earth, steel, or concrete dikes. The type of containment system best suited for a particular facility depends on the consequences associated with an accidental release from that location. The inventory of toxic material and its proximity to other portions of the plant and to the community are primary considerations in the selection. The secondary containment system should be able to contain spills with a minimum of damage to the facility and its surroundings and with minimum potential for escalation of the event.

In general, secondary containment systems:

- Prevent the spread of hazardous liquid from the immediate spill area to nearby areas;
- Limit the size of the pool of spilled liquid;
- Reduce the rate and quantity of vapor generated;
- Prevent hazardous vapor concentrations from spreading to areas outside the facility boundary; and
- Prevent the material from reaching a source of ignition, if it is flammable.

The most common type of secondary containment for storage and process vessels is a low-wall dike (14). A dike, which is a physical barrier around the perimeter of process equipment or storage vessels, is designed to confine the spread of liquid spills. A dike can be little more than a curb or a high wall rising to the top of a storage tank. It can be constructed of earth, steel, or concrete. Figure 7-5 shows a typical use of a dike.

The area contained by the dike is usually sufficient to contain the largest tank or process unit served. Generally, a limited number of process units or storage tanks are enclosed within one diked area; as the number of units increases, so also does the risk of an accidental release.

For most applications, dike heights range from three feet to twelve feet, depending on the area available to achieve the required volumetric capacity (15). For a specific capacity, a low-wall dike requires the greatest amount of land area but is usually the least expensive to construct. On the other hand, higher wall dikes may cost more but they may also result in some vapor holdup and contribute to a reduction in the size of the vapor cloud (5).

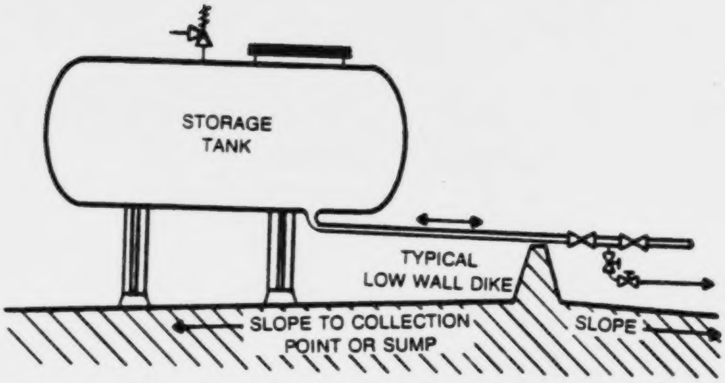

STORAGE
TANK
TYPICAL
LOW WALL DIKE
SLOPE TO COLLECTION
POINT OR SUMP
SLOPE

Figure 7-5. Conceptual diagram of a typical low-wall dike.

Dike walls are designed to be liquid tight and to withstand the hydrostatic pressure and temperature of the spill. Dikes are typically located a sufficient distance from the tank to allow access to the vessel and to equipment near the vessel. Piping is routed over dike walls; penetrations through walls are avoided if possible. Vapor fences may be situated on the top of the dikes to give additional vapor retention capacity. In addition, if there is more than one tank or process vessel in the diked area, the vessels are often elevated above the maximum level attainable in the impoundment if more than one tank or vessel loses its entire contents. Common diking of incompatible materials should be avoided.

Provision should be made for draining rainwater from diked areas. This will involve the use of sumps and separate drainage pumps, since direct drainage to stormwater sewers would allow any spilled material to follow the same route. Alternatively, a sloped rain hood may be used over the diked area that could also serve to direct the rising vapors to a single release point.

In areas where it is critical to minimize vapor generation, surface insulation may be used in the diked area to further reduce heat transfer from the floor and walls or the dike to the spilled liquid. In addition, earthwork dikes may require a layer of clay, asphalt, plastic film, or similar material to prevent the contained material from seeping into the ground (4).

The ground enclosed within a dike should be graded to cause the spilled liquid to accumulate at one side or in one corner. This will help minimize the area to which the liquid is exposed and from which it may gain heat.

High-wall dikes may be an appropriate secondary containment choice for selected systems (8). High-wall dikes may be constructed of low-temperature steel, reinforced concrete, or prestressed concrete. A weather shield may be provided between the tank and wall, with the annular space remaining open to the atmosphere. The available area surrounding a storage tank will dictate the minimum height of the wall. High-wall dikes may be designed with a volumetric capacity greater than that of the tank or vessel to provide vapor containment. Increasing the height of the wall also raises the elevation of any released vapor.

As with low-wall dikes, piping should be routed over the wall if possible. The closeness of the wall to the tank may necessitate placement of the pump outside the wall, in which case the outlet (pump suction) line will have to pass through the wall. In such a situation, a low dike encompassing the pipe penetration and pump may be provided, or a low dike may be placed around the entire wall.

An alternative to simply accumulating the material in one corner of the diked area is to provide a system such as the one depicted in Figure 7-6, which consists of a concrete or steel basin located at the lower edge of the dike. A one-way valve allows the toxic material to flow into but not out of the basin. A submerged pump is used to remove the material from the basin, and it is either sent to storage or to an appropriate treatment and disposal system. In addition, the vapor generated from the spilled liquid could be sent to a scrubber or flare. Such basins may be required to conform to regulations for underground storage of toxic chemicals.

A remote basin is another type of secondary containment. It is especially well suited to storage systems where more than one tank or process vessel is served and a relatively large site is available. The flow of a liquid spill is directed to the basin by dikes and channels under the storage tanks. These channels are designed to minimize exposure of the liquid to other tanks and surrounding facilities. Often the channels that lead to the remote basin, as well as to the basin itself, are covered to reduce the rate of evaporation of the spilled liquid. For nonflammable materials, the impounding basin is usually located near the tank to minimize the amount of toxic material that evaporates as it travels to the basin. For flammable materials, two conflicting spacing requirements must be considered. First, the impounding basin must be close to the tank to minimize evaporation. Second, the impounding basin must be far enough from the tank that a fire in the basin would not expose the tank to excessive heat.

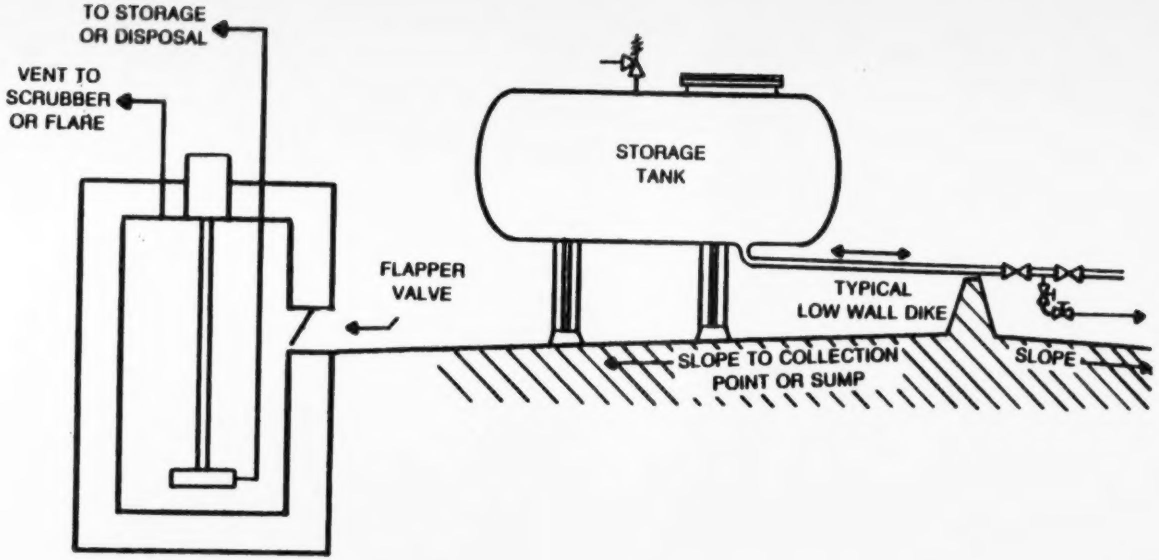

TO STORAGE OR DISPOSAL
VENT TO SCRUBBER OR FLARE
STORAGE TANK
FLAPPER VALVE
TYPICAL LOW WALL DIKE
SLOPE TO COLLECTION POINT OR SUMP
SLOPE

Figure 7-6. Conceptual diked storage facility with integrated containment sump.

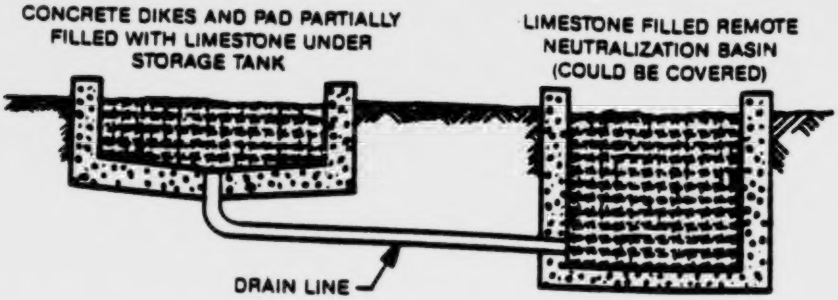
A neutralization basin is an alternative to an impounding basin. This system is essentially the same as the impounding basin, except that the spilled material is mixed with a neutralizing material to form a mixture that can then be disposed of safely (9). For acidic materials, an appropriate material might be lime, which could be stored in the basin as a premixed slurry or as solid limestone. However, a high heat of reaction may cause an increased rate of evaporation with some materials. For example, Figure 7-7 illustrates two layouts for a neutralization basin.

A final type of secondary containment is one structurally integrated with the primary system to form a vapor-tight enclosure around the primary container (15). Many arrangements are possible. A double-walled tank, as illustrated in Figure 7-8, is an example of such an enclosure. A low-wall dike placed around the entire systems may be used as a backup, in the event of wall or foundation failure.

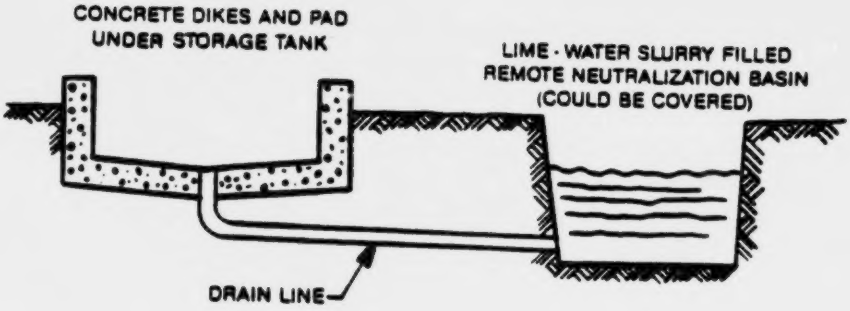
7.3 APPLICABILITY AND PERFORMANCE

7.3.1 Applicability and Performance of Leak-Plugging Devices

The leak plugging and patching techniques listed in this section cannot be used for catastrophic failures of equipment. They perform best on small leaks and most will work better on circular holes than on cracks. Four other limitations common to most of these techniques are: first, personnel must be able to get close enough to the leak to apply the patch or plug; second, it is difficult to prevent the person applying the leak from being sprayed with the leaking material; third, all of these techniques have limited capabilities: no appropriate leak-plugging technique may be available at the time of a specific release situation; finally, all of these techniques require time to set up and implement, and a large amount of hazardous material may escape before the leak can be stopped. It could be very hazardous to attempt to plug the flow of a flammable material. Plugging such a leak would probably require personnel to enter a cloud of material within the flammable range.


CONCRETE DIKES AND PAD PARTIALLY FILLED WITH LIMESTONE UNDER STORAGE TANK
LIMESTONE FILLED REMOTE NEUTRALIZATION BASIN (COULD BE COVERED)
DRAIN LINE

LIMESTONE NEUTRALIZATION BASIN


CONCRETE DIKES AND PAD UNDER STORAGE TANK
LIME - WATER SLURRY FILLED REMOTE NEUTRALIZATION BASIN (COULD BE COVERED)
DRAIN LINE

LIME WATER NEUTRALIZATION SYSTEM

Figure 7-7. Conceptual diagram of potential layouts for a remote neutralization basin system.

Source: Adapted from Reference 9.

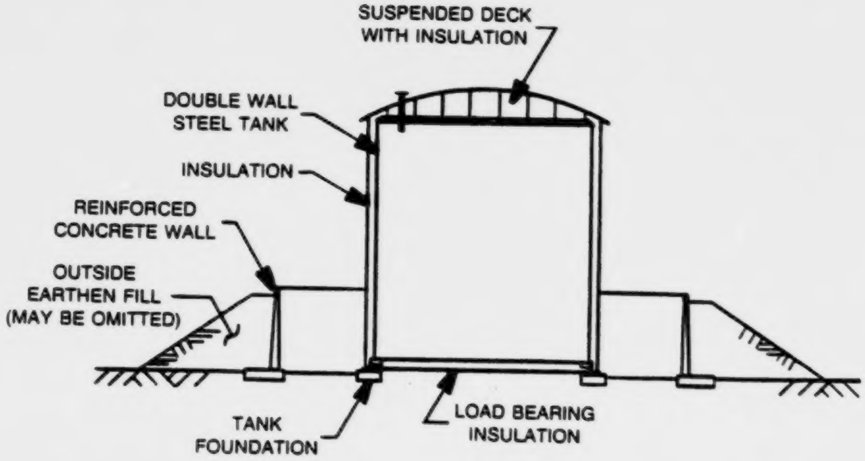

SUSPENDED DECK
WITH INSULATION
DOUBLE WALL
STEEL TANK
INSULATION
REINFORCED
CONCRETE WALL
OUTSIDE
EARTHEN FILL
(MAY BE OMITTED)
TANK
FOUNDATION
LOAD BEARING
INSULATION

Figure 7-8. Conceptual diagram of a double-walled tank system.

Source: Adapted from Reference 15.

Where hazardous materials are involved, a patch or plug should never be regarded as a permanent form of repair. The purpose of leak plugging is to stop the leak just long enough to shut down the process, drain the storage tank or effect whatever changes are necessary to stop the flow of material upstream of the release.

Chemical Patches and Plugs--

A limited amount of experimental testing has been done to measure the performance of chemical patches and plugs. One report prepared by the Environmental Protection Agency summarized the results of leak-plugging tests on a variety of expanding foams and nonexpanding sealants (5). In these tests, the plugging chemical was pushed into the leak and held in place until it hardened. Table 7-1 shows some of the test results. The EPA report also calculated a practical applicability range where chemical plugs might be used; Figure 7-9 shows this range.

Chemical patches and plugs have several advantages over alternate plugging techniques: the plug can conform to irregularly shaped holes and cracks; the plug can be applied to holes in irregularly shaped surfaces; and no elaborate application devices are required. One disadvantage of chemical plugs is that the chemical plugging material must be resistant to attack by the chemical that is escaping; a facility may need to have several different plugging materials on hand. In addition, a chemical plug will be subject to failure by chemical attack or physical or thermal shock.

Several studies have tested the performance of applicators that use a foam-filled elastomer or fabric bag for leak plugging (6,7). Using such a device increases the physical strength of the plug. Also, since a narrow lance is first inserted into the hole, less spray of leaking material may occur than with other methods, thus reducing the risk of exposure to personnel. The disadvantages of using this type of applicator are the same as those associated with the use of chemical patches without an applicator. The

TABLE 7-1. HAZARDOUS CHEMICALS TESTED AND SMALL-SCALE SEALING TEST RESULTS

Hazardous Material	Results of Sealing Tests		
	Starfoam® Urethane Foam	Sea-Goin® Epoxy Putty	Other Successful Sealants
Phenol	Sealed (A)[+][*]	Failed (A)	Butyl Rubber (A)
Methyl Alcohol	Sealed (A,W)	Sealed (A,W)	Epoxy Putty (A) MSA Urethane (A)
Insecticides, Rodenticides:			
DDT 95% Solu./Water		Sealed (W)	
Dieldrin	Sealed (A)	Sealed (A)	
Acrylonitrile	Failed (A)	Failed (A)	Polysulfide Rubber (A)
Chlorosulfonic Acid		Failed (A)	
Benzene	Sealed (A,W)	Sealed (A,W)	MSA Urethane (A,W)
Phosphorus Pentasulfide		Failed (A)	
Styrene	Sealed (A)	Sealed (A)	
Acetone Cyanohydrin		Sealed (A)	
Nonyl Phenol	Sealed (A,W)	Sealed (A,W)	
Isoprene	Sealed (A)	Sealed (A)	
Xylene		Sealed (A)	
Nitrophenol	Sealed (W)	Sealed (W)	

[+] Sealed leaks of aqueous solutions (50 to 90 percent) for 18 hours, then failed.

[*] "A" and "W" indicate tests performed in air and submerged in water, respectively.

Source: Reference 5

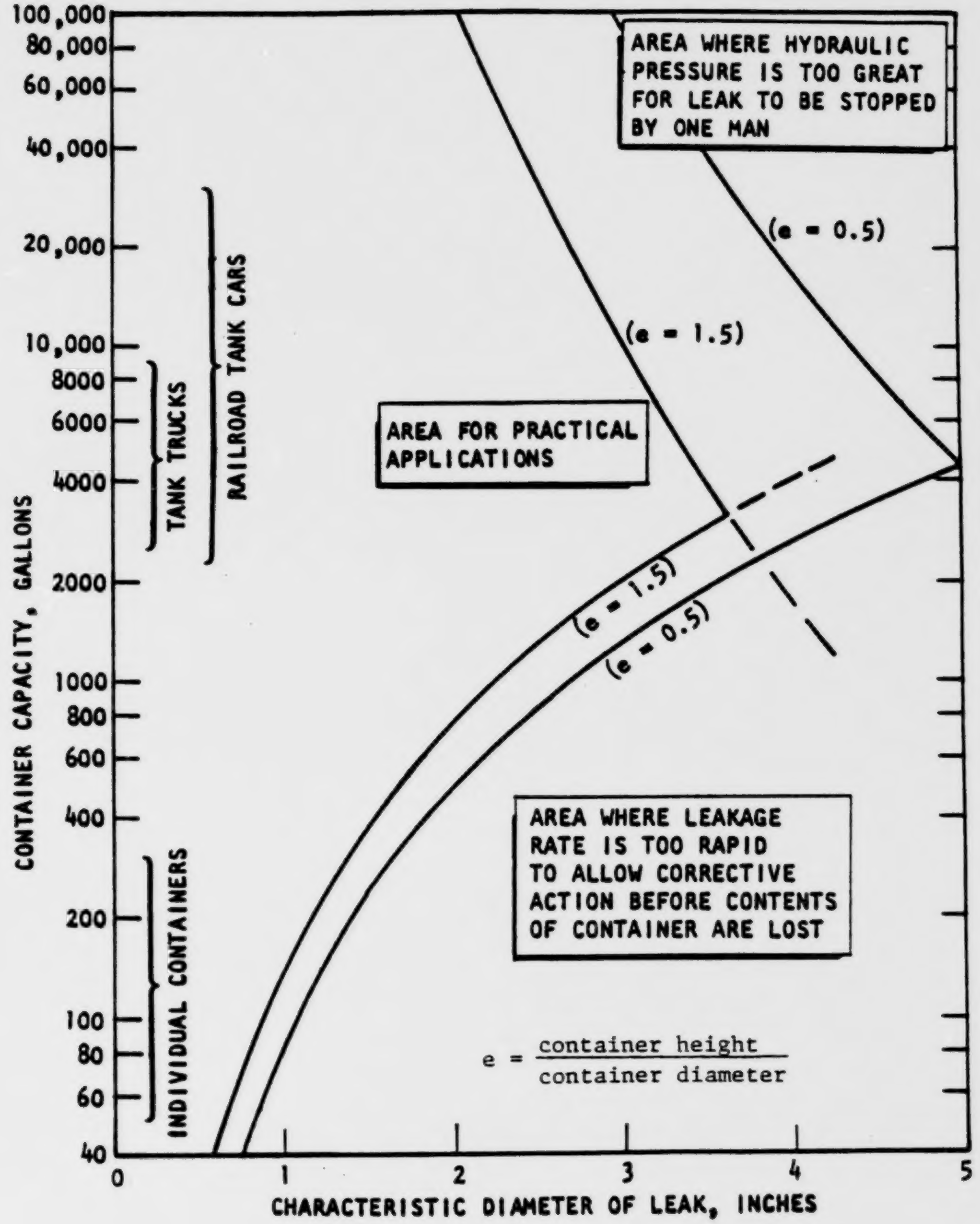


Figure 7-9. Envelope of practical applications for sealing leaks in nonsubmerged containers.

Source: Reference 5.

applicator. The plug is still subject to failure by chemical attack or thermal or physical shock.

Physical Patches and Plugs--

The primary advantage of physical patches and plugs is their ability to form a very tight seal nearly as strong as the original container. They can be constructed of material more resistant to chemical attack than a chemical plug.

The primary disadvantage of physical leak-repairing devices is that most are designed for a very specific use. For example, a leak from a flange can be stopped by using a specially designed encasement constructed to form a tight seal around the entire flange; this is a very effective method for stopping leaks. However, such an encasement will work only for flanges and often a different encasing device will be required for each size of flange. A facility would need a large inventory of physical plugging devices to be able to handle any accidental release that might occur; this is an impractical solution for most situations.

Physical patches and plugs are most useful where only a few types of leaks are possible, or where only a few types of leaks present the greatest potential hazard. For example, the Chlorine Institute has assembled leak repair kits for several transportable chlorine storage containers. The kits contain leak-repairing devices for all the types of leaks most likely to occur in each of the containers (5 to 9 different types of leaks).

Leak-plugging methods where a physical jacket or shell is filled with a chemical plugging material have some advantages over other types of devices. The outer shell provides high physical strength for the plug. Also, the use of the chemical sealing material, means that the shell does not have to form a tight seal around the leaking equipment; therefore, one type of shell could be used for plugging leaks from several line sizes or for several types of fittings.

One disadvantage of this method is that the chemical plugging material must be chemically resistant to the leaking material and must be thermally resistant to the temperature of the leaking material. These types of devices are used for plugging leaks from pipes or other small diameter fittings by enclosing the entire line. They are not used for filling a leak, and thus are not practical for leaks from large diameter vessels.

Methods for Stopping Flow Upstream of a Leak--

The main advantage of any method that stops the flow of material upstream of a leak is that it reduces the potential of personnel exposure. However, all of these methods have severe limitations that restrict their usefulness in the event of an accidental release.

Some technical literature addressing the use of pipe freezing for plugging lines has examined the utility of pipe freezing for maintenance purposes (15). Many organic materials cannot form a frozen plug with the strength sufficient to stop flow. Many materials will require extremely low temperatures to create a solid plug. Even if a material can form a physically strong plug at an achievable temperature, the method would probably require too much time to implement in the event of an accidental release.

Stoppling and line shearing and sealing techniques have the advantage of forming a mechanically tight seal. These are proven methods that have a low potential for exposing personnel to the leaking material. The disadvantage of the methods is that they require elaborate and expensive equipment. Usually, a company that specializes in this work is contracted to plug a line. Such an arrangement would not be practical in the event of an accidental release because of the time required for the plugging equipment to be brought to the site.

7.3.2 Applicability and Performance of Physical Barriers and Containment Systems

Secondary containment systems can minimize the spread of a liquid spill and/or the rate of toxic vapor generated from an accidental release. However, the type of containment system best suited for a particular storage or process unit will depend on the material being contained and on the risk associated with an accidental release from that location. This subsection discusses the factors that must be examined when selecting a secondary containment system.

In general, it is desirable to use some form of secondary containment around storage facilities to prevent the unconfined spread of spilled liquid. It is also beneficial to slope the surfaces away from storage tanks to a catch basin so that liquid does not accumulate in the dike but is still confined to an area near the dike. This is especially important if the material is toxic and flammable, since an ignited pool of liquid beneath a vessel could lead to a BLEVE (boiling liquid expanding vapor explosion).

In process areas, curbing around accumulators, reactors, or other vessels containing large amounts of liquid serves to prevent the unconfined spread of spilled liquid. For piping systems, the question of whether or not to provide secondary containment depends partly on the pressure and temperature of the material in the pipes and on the location of the piping system. Curbing or trenches may be used along long pipe runs if a break could result in a large accumulation of liquid. However, in such situations the curb or dike should be designed to drain liquid away from the pipe. For a long pipe carrying flammable materials this will reduce the potential for small leaks to result in the accumulation of flammable materials around the pipe. Transfer areas represent high-hazard areas because of the failure of temporary connections used during transfer. Spills may occur frequently and a method of secondary containment may be warranted.

Each situation must be specifically examined. The secondary containment system should at least be able to contain spills with a minimum of damage to the facility and its surroundings and with a minimum potential for escalating the event.

The applicability of diking to spills of volatile liquids is readily apparent. By containing the liquid, the dike reduces the surface area available for evaporation, at the same time allowing a liquid to be cooled by evaporation so that the vapor release is diminished. In this way, diking can reduce the rate at which a toxic material is released to the air. The material can be allowed to evaporate at a manageable rate, collected into alternate containers, or neutralized in place. A dike with a vapor fence will give extra protection from the wind and will be even more effective at reducing the rate of evaporation.

A dike will not reduce the impact of a gas or vapor release. A dike also creates the potential for toxic material and trapped water to mix, and, depending on the material, this may accelerate the rate of evaporation or the formation of highly corrosive solutions. If materials that would react violently with the released toxic material are stored within the same diked area, the dike will increase the potential for mixing the materials in the event of a simultaneous leak. A dike also limits access to the tank during a spill.

High-wall diking, on the other hand, can be used to minimize vapor generation rates and to protect the tank or vessel from external hazards such as missiles from nearby explosions. Maximum vapor generation rates will generally be lower for high-wall dikes than for low-wall dikes or remote impoundments because of the reduced surface contact area. Insulation on the wall and floor within the annular space can further reduce these rates.

One disadvantage of high-wall impoundments is that the high walls around a tank or vessel may hinder routine external observation. Furthermore, the closer the wall is to the tank or vessel, the more difficult it becomes to reach the tank or vessel for inspection and maintenance.

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A remote basin, on the other hand, allows for removal of the spilled liquid from the immediate tank or process area, allows access to the tank during the spill, and reduces the probability that the spilled liquid will damage the tank, vessel, piping, electrical equipment, pumps, or other equipment. In addition, a covered impoundment will reduce the rate of evaporation from the spill by protecting it from wind or from heating by sunlight.

A limitation of a remote basin is that the potential still exists for water or other incompatible materials to be trapped in the impoundment and mix with the spilled material. Additionally, remote basins do not reduce the effects of a gaseous toxic release.

The effectiveness of a secondary containment system will depend on the specific material being contained. For some liquefied gases, such as chlorine, a spill from a pressurized storage or process vessel results in a significant amount of flashing and vapor generation and little liquid accumulation (14). In such cases, conventional low-wall diking may not be effective. All flashing gases "self-refrigerate" to some extent, and there will likely be some liquid accumulation. Low-wall diking can be constructed around a liquified gas tank in an area too small to contain the whole tank volume, since some will flash off, and a reduction in vapor evolution should be achieved. On the other hand, during releases of pressurized liquefied gases with higher boiling points or during releases of refrigerated liquefied gases, liquid will accumulate near the release point. In these cases, diking will be effective. Each situation must be examined in detail to determine the most appropriate applicable secondary containment system.

A limited amount of data is available concerning the performance of the various types of secondary containment systems. However, dispersion modeling can be used to illustrate the effects of diking and vapor holdup.

For example, a leak from a vertical 10,000-gallon refrigerated storage tank containing chlorine was modeled using the Complex Hazardous Release Model (CHARM®) of Radian Corporation. The chlorine was stored at -40°F and one atmosphere of pressure with a surrounding ambient temperature of 78°F. Vapor dispersion patterns for the following scenarios were investigated:

- Spill of chlorine directly onto soil from a 2-inch hole and allowed to spread unconfined; and
- Spill of chlorine directly onto soil from a 2-inch hole, confined in a 25-foot diameter.

The results of the modeling are presented in Figures 7-10 and 7-11. The results are based on a westerly wind of 10 mph and atmospheric conditions not conducive to mixing and dispersing gas or vapor clouds. Similar results were obtained by Eidsrick (16) for a ruptured pipe containing refrigerated propane.

Figures 7-10 and 7-11 show that confining the spill with a dike dramatically reduces the size of the vapor cloud by limiting the spread of the spill and reducing the surface area available for evaporation.

This example shows the potential effectiveness of a secondary containment system. In general, the effectiveness of any system depends on the properties of the particular chemical being contained and on the properties of the system itself. The secondary containment system should be able to contain spills with as little damage to the facility and its surroundings as possible and with a minimum potential for escalation of the event.

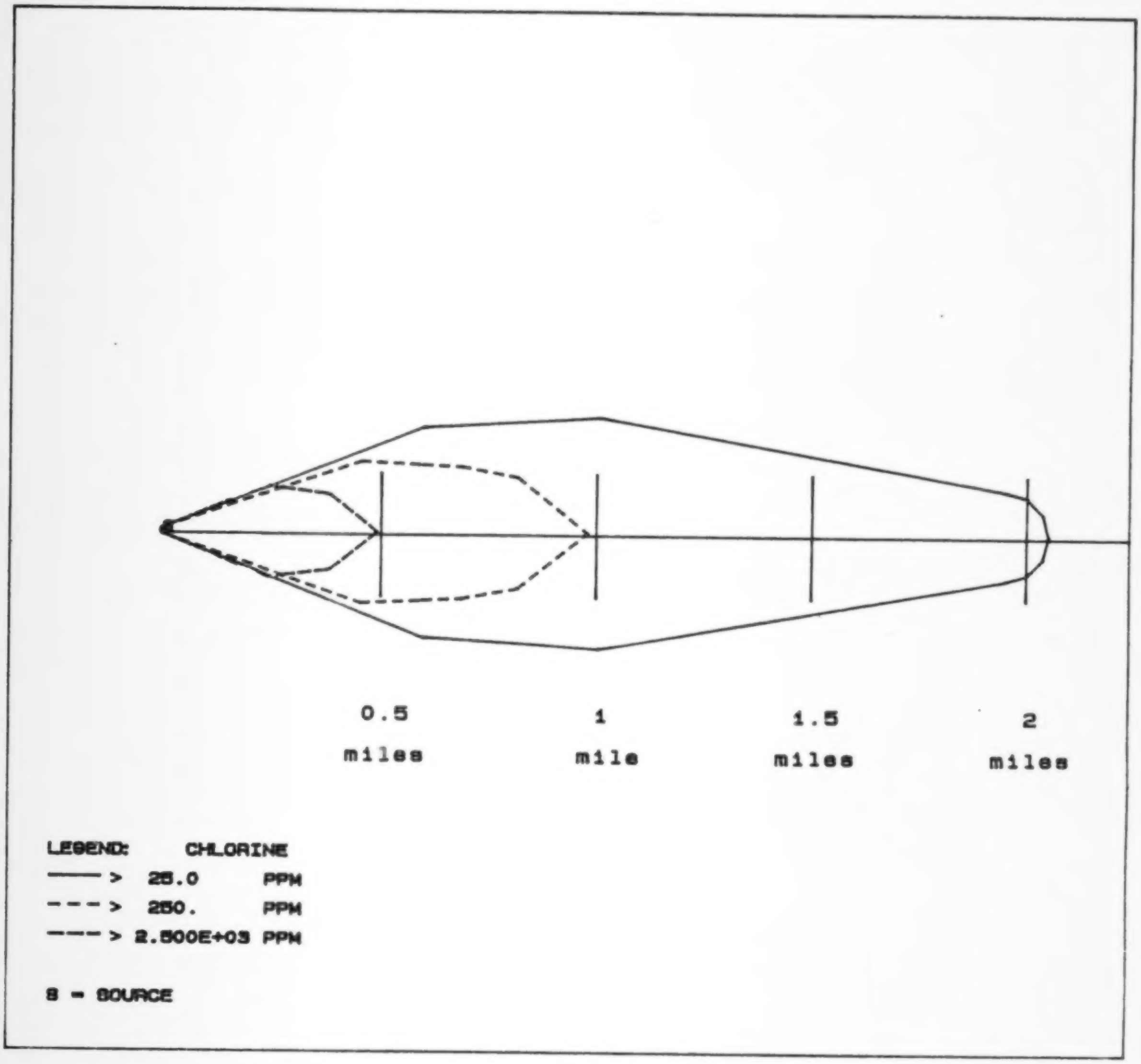

Figure 7-10. Vapor dispersion patterns for a release of chlorine from a 2-inch hole in a 10,000 gallon refrigerated storage tank using CHARM® model.

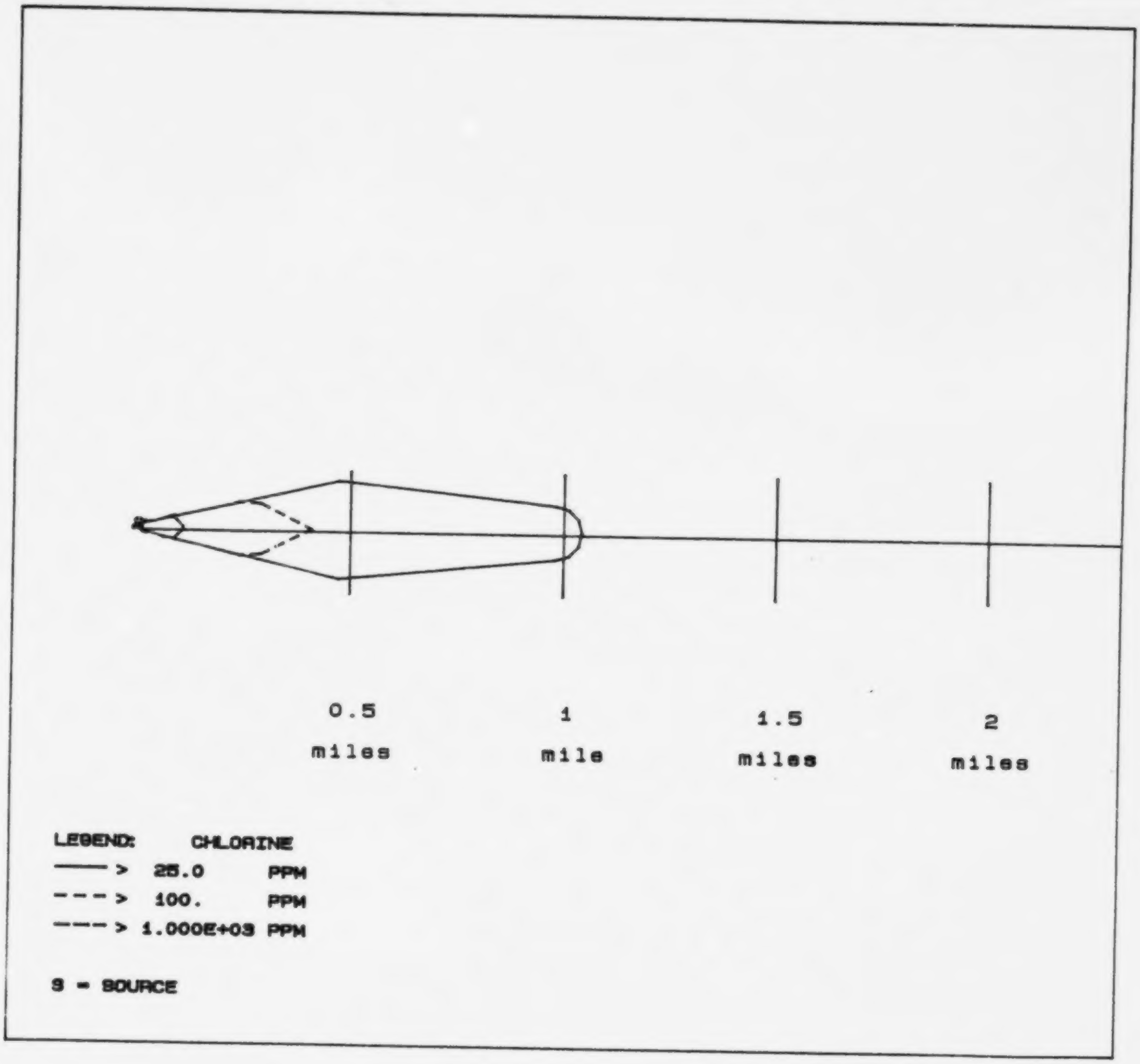

Figure 7-11. Vapor dispersion patterns for a release of chlorine from a 2-inch hole in a 10,000 gallon refrigerated storage tank surrounded by a 25-ft diameter dike using Charm® model.

7.4 RELIABILITY

7.4.1 Reliability of Leak-Plugging Techniques

A qualitative evaluation of the reliability of a leak-plugging device can be based on the ability of the method to securely stop the flow of material from a leak. Reliability could also be assessed in terms of how quickly a leak can be stopped in the event of an accidental release.

Chemical patches and plugs can be applied to a leak relatively quickly. In most cases, some equipment will be required to generate the plugging compound. Since this equipment may sit idle for very long periods of time, routine inspection and maintenance of the equipment will be required to maintain a quick response time.

Chemical patches and plugs are mechanically and chemically weak when compared with other leak repair methods. Vibration, shock, or high pressure can all result in the failure of a chemical plug. These plugs are also subject to failure when exposed to high temperatures or to chemically incompatible materials.

Mechanical patches and plugs can be applied to a leak relatively quickly. They form seals that can sometimes have the structural strength of the original process equipment; however, mechanical vibration, shock or improper application can cause a mechanical leak plugging device to fail.

Methods for stopping the flow of material upstream of a leak are characterized by long preparation and implementation times. Once in place, however, these methods are reliable ways of stopping flow.

7.4.2 Reliability of Physical Barriers and Containment Systems

The reliability of a secondary containment system is directly related to how it is designed and constructed. In particular, the reliability will be affected by the following:

- Ability to withstand the hydrostatic pressure and temperature of a spill;
- Ability to withstand the dynamic stresses caused by fire or explosion, in the case of flammable materials; and
- Ability to withstand damage caused by earthquakes, floods, high winds, frost, or similar events.

Systems must be inspected and maintained regularly. Undetected corrosion and cracks in dike walls, for example, could lead to the failure of a secondary containment system during an accidental release.

7.5 SECONDARY HAZARDS

7.5.1 Secondary Hazards of Leak-Plugging Techniques

All leak-plugging techniques can potentially expose plant personnel to the leaking material. Often, material flowing from a leak will spray out around the plugging device as it is being applied. Also, where flammable vapors are involved, these personnel will probably have to enter a flammable gas cloud when applying the plug.

Where hazardous materials are involved, a temporary leak repair should never be treated as a permanent fix. Once the leak has been plugged, actions should be taken to shut down the portion of the process involved with the release so that permanent repairs can be made.

7.5.2 Secondary Hazards of Physical Barriers and Containment Systems

Mixing incompatible materials is one potential secondary hazard associated with most types of secondary containment. This is a particular problem where water-reactive materials are stored within the containment area. Rainwater can collect in diked areas or in containment basins. Spilled materials could mix with the water in the event of an accidental release. Though not so likely, two incompatible chemicals could mix if they were both stored within the same secondary containment area, and if both were released simultaneously.

A spill from a vessel surrounded by a dike can fill up the dike to a level that prevents access to the vessel, which could prevent repair or emergency response crews from stopping the release at its source. Also, a fire in this situation would expose the vessel to extreme heat, which could result in an explosion. For both of these reasons, dikes should be designed so that material accumulates away from vessels within the dike.

A covered collection basin can trap flammable vapors when a liquid is involved. Fire could spread to such a basin and result in an explosion.

7.6 COSTS

Table 7-2 presents some order-of-magnitude costs for a few leak-plugging devices. These costs are for equipment only and do not include installation.

Although the variety of types and sizes of secondary containment systems makes it difficult to estimate costs, costs for dikes built around storage facilities can be estimated easily. The cost of a rectangular dike can be expressed as (17):

$$\mathrm{COST} = (aD^2 - \pi r^2)F + 2(1 + a)DHW$$

TABLE 7-2. COSTS OF VARIOUS LEAK PLUGGING DEVICES (1986 Dollars)

Equipment Item	Cost ($)	Reference
Small transportable polyurethane foam system	5,000 - 8,000	18
Chlorine Institute Emergency Repair Kit for Chlorine Cylinders	800	1
Chlorine Institute Emergency Repair Kit for Chlorine Ton Containers	900	2
Chlorine Institute Emergency Repair Kit for Chlorine Tank Cars and Tank Trucks	1,000	3
Stainless steel band clamp, for leaking 4" pipe, working pressure less than 150 psi	100	12
Carbon steel bolted sleeve, for leaking 4" pipe, working pressure less than 1000 psi	500	18
Clamp for sealing pinhole leaks on a 4" pipe, working pressure less than 1000 psi	70	18

where:

a - ratio of dike length to dike width
D - dike width
r - tank radius
H - dike height
F - cost of dike floor per unit area
W - cost of dike wall per unit area.

In general, the cost of secondary containment systems will be small compared with the costs associated with the vessels that they protect. Besides the initial investment, additional costs are associated with the necessary cleanup equipment needed such as pumps, for example, when a release occurs within the containment systems.

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SECTION 8

SPRAY, DILUTION, AND DISPERSION SYSTEMS

Water spray systems are routinely used in the chemical process industries for a variety of fire protection purposes. However, they can also be used to reduce the effects of toxic and/or flammable gas or vapor releases. Theoretical studies and experimental research have shown that such sprays can be effective in aiding the dispersion and dilution of gas or vapor clouds resulting from an accidental release (1,2,3,4,5,6,7,8). However, many of the results are based on specific systems operating under a specific set of conditions. Details concerning the overall effectiveness of these systems are limited in scope. Additional research in this area is needed to refine the present data.

Steam curtains are another technique for reducing the effects of toxic and/or flammable gas/vapor releases. Steam curtains act similarly to water sprays in that the primary dispersing mechanism is the dilution of the gas or vapor with air. However, steam curtains provide enhanced buoyancy to the toxic and/or flammable cloud by heating the gas or vapor passing through the steam curtain.

This section of the manual presents a detailed discussion of the use of water spray systems and steam curtains for the mitigation of toxic and/or flammable gas or vapor releases. Both mobile and fixed installations are discussed in terms of their applicability, performance capabilities, reliability, secondary hazards, and costs. In addition, reactive spray systems are briefly discussed.

8.1 BACKGROUND

8.1.1 Spray Systems

A spray is defined as a dispersion of liquid droplets in a gas. Sprays can achieve a variety of objectives, including, but not limited to, the forced dispersion and dilution of a gas or vapor, absorption of water-soluble materials, confinement of released vapor or gas in a particular area, or diversion of the vapor or gas away from a particular area.

In mitigating toxic and/or flammable gas or vapor releases, the primary purpose of sprays is to dilute the gas or vapor with air. This is brought about by the entrainment action of the sprays. The momentum and energy of the spray causes air to be pulled into the cloud and creates momentum and turbulence in the gas or vapor, thus improving mixing and enhancing dilution. The performance of a spray depends in part on the drop size distribution. Fine droplets lose their momentum quickly and move large volumes of air relatively slowly. Coarse droplets entrain less air but induce greater velocities.

Dilution is also achieved to a lesser degree by absorption of the gas in the liquid drops. Gases that are highly soluble in water (e.g., ammonia) can be partially absorbed by a water spray. However, the mass transfer characteristics of the system may limit the efficiency of absorption; it is difficult to create a sufficiently high liquid-to-gas ratio using sprays. A "fog" consisting of fine water droplets often improves the mass transfer efficiency. Adding a chemical to the spray solution that reacts with the vapor can improve the absorption efficiency. An example would be using an alkaline spray solution to absorb an acidic vapor release.

Finally, spray-induced warming of cold vapor clouds that form from liquefied gas releases can enhance the dilution of a heavier-than-air cloud. The individual water drops transfer heat to the cloud, thereby increasing both the buoyancy of the gas and its dispersal.

In addition to dilution, liquid sprays are also useful for containment and diversion. In some situations, the movement of vapor clouds, especially if visible because of aerosol formation or condensation of moisture, can be controlled by hand-held nozzles and fire monitors. A released gas cloud may also be contained in a particular area by a series of spray nozzles around the perimeter.

8.1.2 Steam Curtains

As with water sprays, the primary purpose of a steam curtain used to mitigate toxic and/or flammable gas/vapor releases is to dilute the gas or vapor with air. The energy of the steam causes air to be pulled into the cloud and creates turbulence in the gas or vapor, thus improving mixing and enhancing dilution.

Steam curtains will also heat the gas cloud and enhance its buoyancy. Heating the cloud will decrease its density and help the cloud to rise from the ground, which can result in decreased ground level concentrations of the toxic vapors downwind of the release.

The following subsection describes spray systems and steam curtain systems that may assist in the mitigation of accidental vapor releases.

8.2 DESCRIPTION

In recent years, increased attention has been focused on the use of aqueous sprays and steam curtains for the control and dispersion of toxic and/or flammable vapor releases. Research studies have revealed that such systems are effective; however, the technology is still in the early stages of development.

8.2.1 Spray Systems

A spray system may consist of a single nozzle, such as a fire monitor, or a series of specially designed nozzles that discharge in a predetermined spray pattern. The type, design, and method of application of spray systems vary, depending on the specific situation. Two systems are most common: fixed water sprays and mobile water sprays. These systems may be used individually or in combination. A reactive water solution is sometimes used with either a fixed or mobile spray system.

Fixed Water Spray Systems--

Fixed water spray installations are similar to fire protection fixed pipe deluge systems. They may be located in the open air or in enclosures where there is a high probability of an accidental release of a toxic and/or flammable gas/vapor or where there is a need to protect a certain area (i.e., a control room). These spray systems are used where there is a need for quick application of water spray.

Fixed installations may consist of a series of spray nozzles elevated off the ground with the spray directed downwards or located at ground level with the spray directed upwards. Figure 8-1 is a conceptual drawing of a typical system using downward spraying nozzles. Two facilities in England have installed such fixed water spray barriers (9); however, they are limited to the control of small scale leaks.

Figure 8-2 shows a system where the spray nozzles completely surround a desired area. The advantage of a completely-surrounding system is that it also provides a degree of containment. However, total spray barrier systems may use excessive quantities of water since upwind sprays will have little effect on the gas cloud. Spray barriers that totally surround a system often are designed so that only downwind sections are activated in the event of a

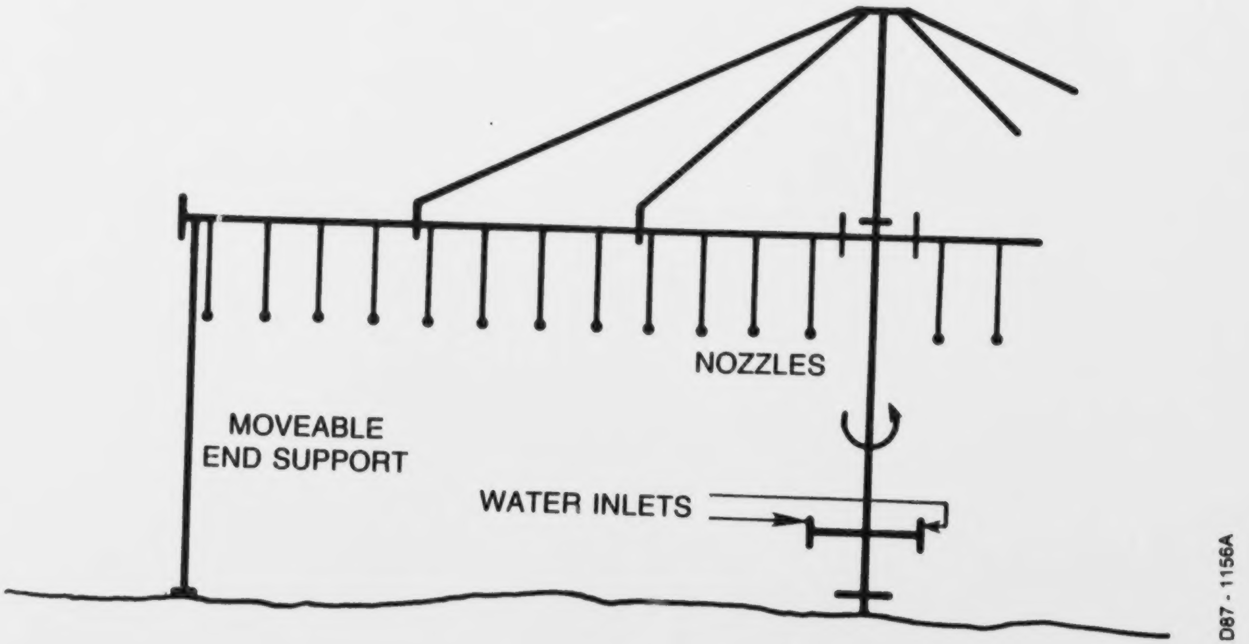
NOZZLES
MOVEABLE
END SUPPORT
WATER INLETS
D87 - 1156A

Figure 8-1. Conceptual diagram of water spray barrier using downward spraying nozzles.

Source: Adapted from Reference 8.

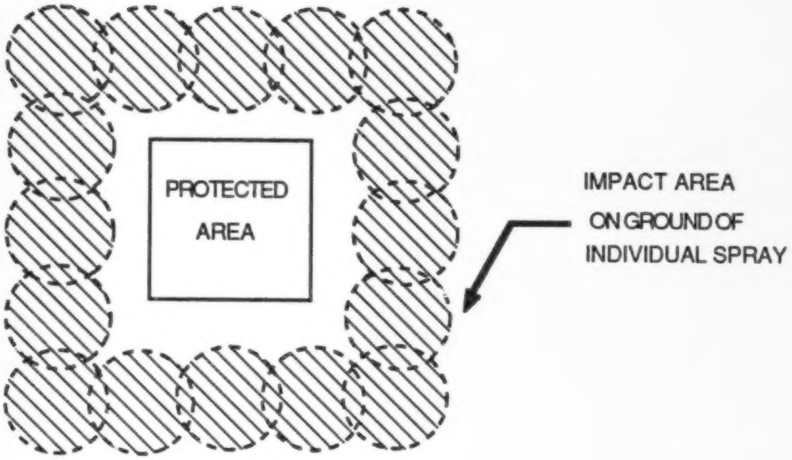
PROTECTED AREA
IMPACT AREA ON GROUND OF INDIVIDUAL SPRAY

Figure 8-2. Conceptual diagram of fixed-spray barrier surrounding protected area.

release, as shown in Figure 8-3. Activation of fixed systems can be manual or automatic (by using gas detectors and switches).

Fixed water sprays incorporated into semi-enclosed structures have also been proposed as a possible mitigation technique, although this is still an experimental concept (10). Figure 8-4 shows such a system. These systems offer several potential advantages over other systems. First, it can provide a degree of direct containment by partially enclosing the released vapors. Second, release of the material occurs at a known location, rate, and concentration.

Thus, if sources with a high-release probability can be identified and the exposed area and release direction can be defined, a properly designed fixed water spray system can be effective in reducing the hazards of an accidental toxic release.

Mobile Water Spray Systems--

A mobile water spray system, illustrated in Figure 8-5, consists of hand-held firefighting nozzles and/or fire monitors. It can be used as an alternative to a fixed water spray system or when a release has moved beyond the reach of a fixed installation.

Mobile water sprays in the form of a "fog" have been used for absorbing and diluting of water-soluble materials. A "fog" is defined as a water spray having a mass median drop diameter of 0.03 in. or less (11). The fine spray or "fog" allows for more effective mass transfer. A technique for controlling ammonia releases has been developed from several hundred outdoor ammonia workshops for firefighters (11). As shown in Figure 8-5, fire hoses and fog nozzles are used to create a "capture" zone downwind of a release by positioning the nozzles in designated locations. This technique was developed for a specific type of release (i.e., an ammonia tank rupture) and thus may not apply in all situations.

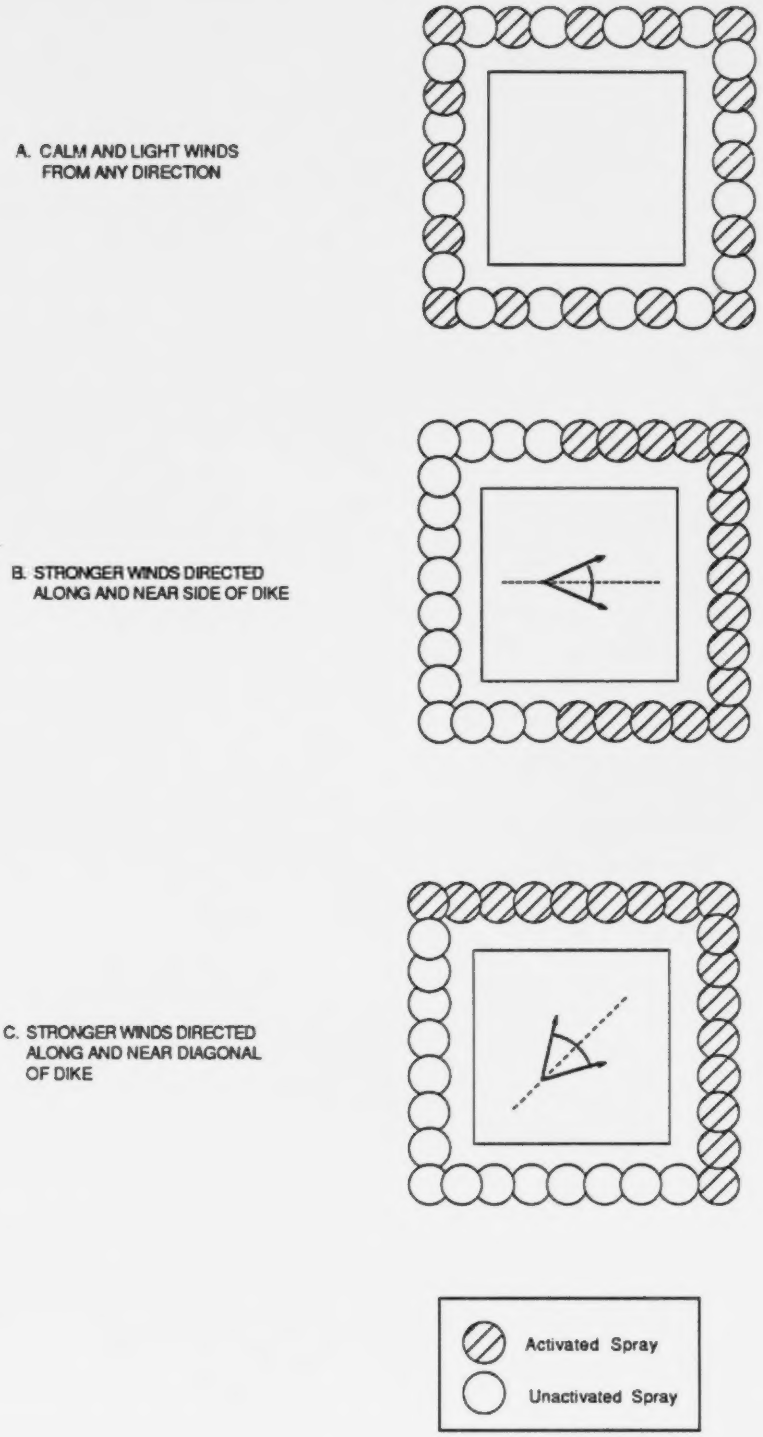
A. CALM AND LIGHT WINDS FROM ANY DIRECTION
B. STRONGER WINDS DIRECTED ALONG AND NEAR SIDE OF DIKE
C. STRONGER WINDS DIRECTED ALONG AND NEAR DIAGONAL OF DIKE
▨ Activated Spray
○ Unactivated Spray

Figure 8-3. Conceptual diagram of fixed-spray barrier with activation according to wind direction.

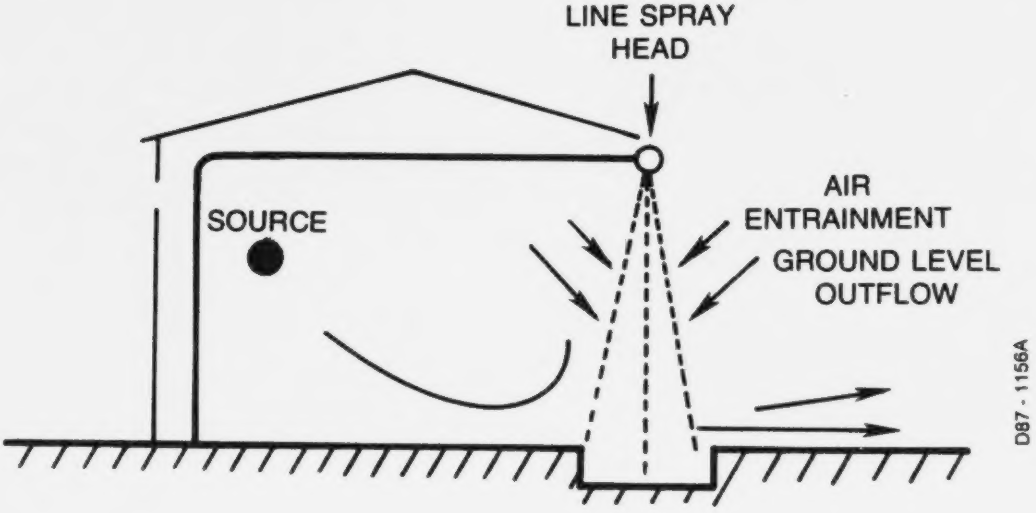
LINE SPRAY HEAD
AIR ENTRAINMENT
SOURCE
GROUND LEVEL OUTFLOW
D87 - 1156A

Figure 8-4. Conceptual diagram of water sprays incorporated into semi-enclosure.

Source: Adapted from Reference 10.

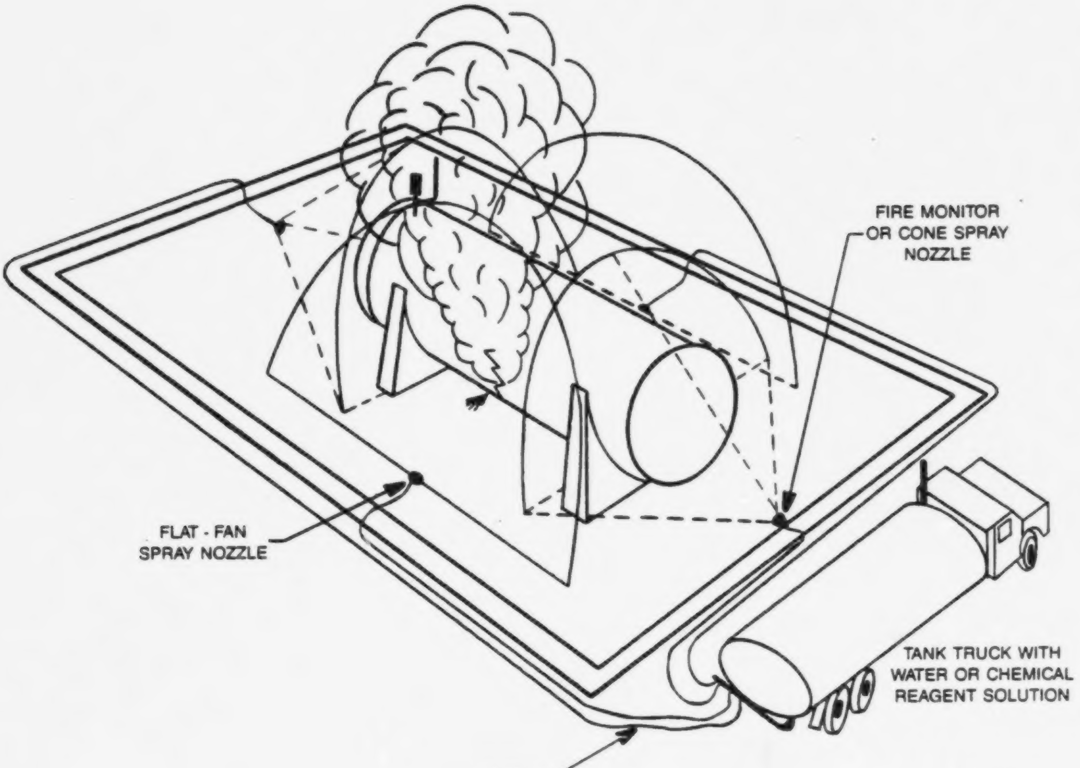
FIRE MONITOR
OR CONE SPRAY
NOZZLE
FLAT - FAN
SPRAY NOZZLE
TANK TRUCK WITH
WATER OR CHEMICAL
REAGENT SOLUTION
HOSES

Figure 8-5. Typical mobile water spray system.

Source: Adapted from Reference 11.

Mobile systems have also been used as effective barriers. In particular, Beresford (12) has developed a system whereby coarse water spray discharging from flat fan sprays and wide-angled spray monitors in an upward direction completely surround a flammable and/or toxic gas leak in the form of a "chimney." This technique is shown in Figure 8-6. Large amounts of air are induced at ground level, and dilution of the gas is achieved as the sprays push the gas out the top of the "chimney" allowing it to disperse safely.

A mobile water spray system must be capable of rapid deployment to the source of a release. In many releases, the worst may be over by the time such a system is operational. However, the cost of mobile systems are usually less than fixed installations since much of the same equipment can also be used for fire protection. In fixed installations, additional piping and nozzles may have to be added to existing fire protection systems. Thus, for very large installations, a mobile system may be the most cost-effective.

Reactive Spray Systems--

An alternative to a water spray system is the use of a mild aqueous alkaline spray system (e.g., reactive spray system). Often the use of water in absorbing and diluting a toxic gas or vapor is limited by the mass transfer characteristics of the system. In addition, dilution of some materials with water sprays results in the formation of highly corrosive mists. A mild alkaline spray would both enhance absorption and act as a neutralizing agent in the case of acid formation.

Limited data are currently available on the use of reactive spray systems. Several major users of phosgene have experimented with ammonia-injected water spray systems at their facilities (13). These systems consist of an ammonia cylinder connected to a water feed line of a water spray system via an injector system. When the spray system is activated, a valve opens allowing ammonia, under pressure, to enter the water line and create the alkaline solution.

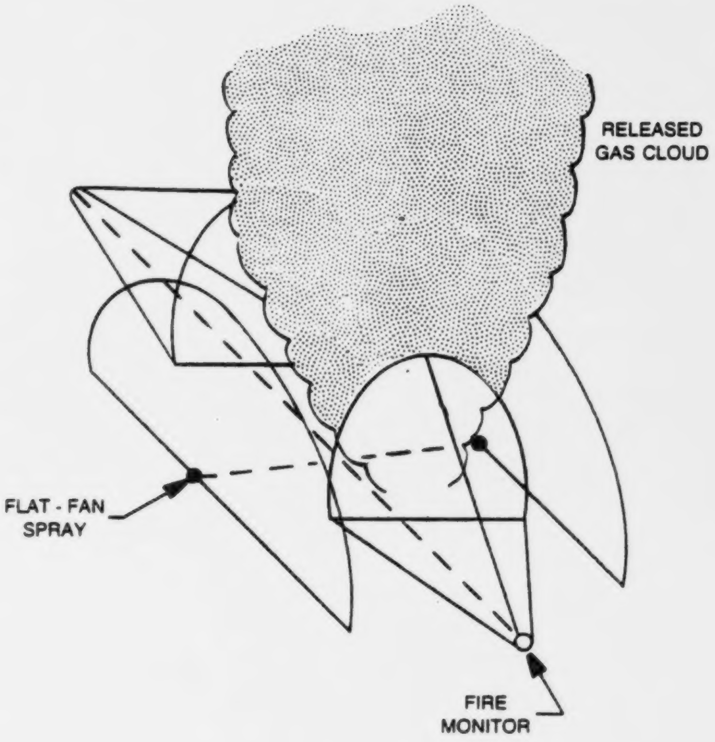
RELEASED GAS CLOUD
FLAT - FAN SPRAY
FIRE MONITOR

Figure 8-6. Conceptual diagram of mobile water spray barrier and associated "chimney" effect.

Other alkaline solutions could also be used. Several examples are sodium carbonate, calcium hydroxide derived from slaked lime, or a weak solution of sodium hydroxide. However, adequate supplies of these solutions would have to be stored or a quick means of production would be required in an emergency situation.

Additionally, the hazards associated with spraying an alkaline solution into the air must be considered. Unless the spray is applied so that the alkaline material remains in a confined area (e.g., a diked storage facility), reactive sprays present an additional health hazard to plant personnel. Also, such sprays may cause the corrosion of machinery and equipment.

In conclusion, reactive spray systems may be more efficient than water sprays in applicable situations. However, more research is needed to define potential applications, performance capabilities, and system design.

8.2.2 Steam Curtains

Steam curtains are fixed-pipe systems used to contain and disperse releases of toxic and/or flammable gas or vapor. Cairney and Cude (14) and Simpson (15,16) have described such systems in detail. A steam curtain consists of a horizontal steam pipe with a row of small holes in the top and mounted near the top of a wall. Figure 8-7 illustrates a typical system. When operated, a wall of steam approximately 15 to 20 feet high is produced. The steam pipe is designed so that all the individual jets combine to form a continuous curtain of steam that entrains sufficient air to dilute the gas or vapor concentration to below its toxic and/or flammable limit. Additionally, the steam pipe is usually divided into sections that are individually supplied with steam from a distribution main, allowing plant operators or an automated activation system to select which sections of the steam curtain will be activated in the event of a release.

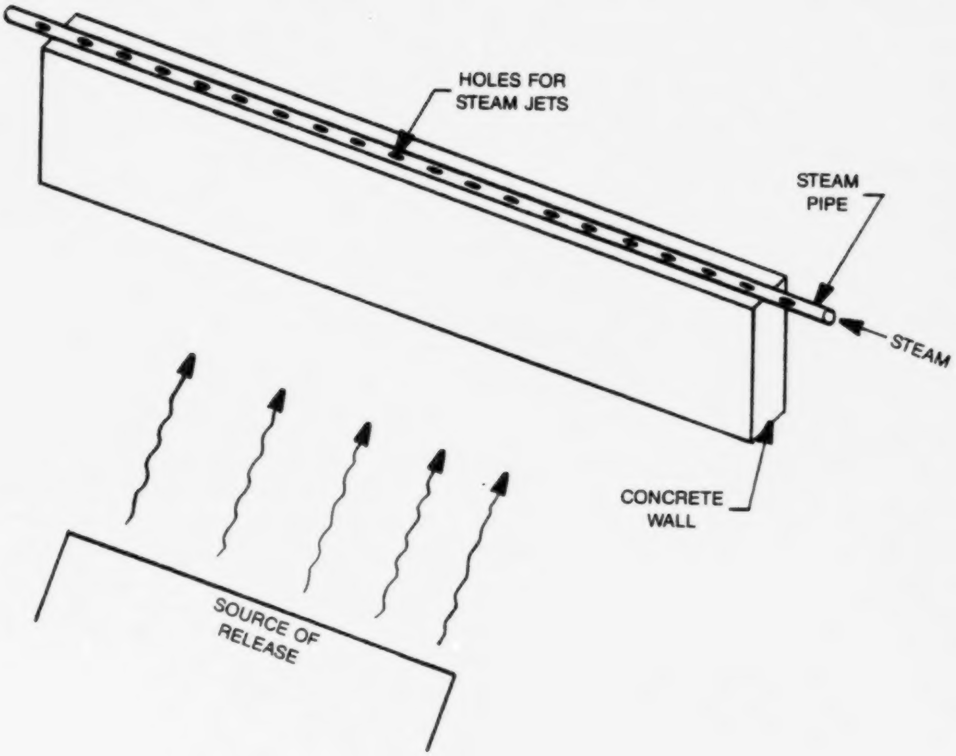
HOLES FOR STEAM JETS
STEAM PIPE
STEAM
CONCRETE WALL
SOURCE OF RELEASE

Figure 8-7. Conceptual diagram of a steam curtain.

The steam curtain can be activated automatically or manually. However, in practice, steam curtains are typically controlled manually by remotely operated valves (17,18).

8.3 DESIGN

8.3.1 Spray Systems

In recent years, much research and a number of experimental studies have contributed to the development of several experimental design methods for water spray systems (6,7,12,19). However, the optimum set of parameters for a particular set of circumstances (i.e., nozzle type, size, location, number, orientation) are not always clear, and, indeed, each situation requires a unique set of parameters. This section of the manual focuses primarily on the circumstances considered in designing water spray systems for mitigating toxic and/or flammable gases and vapors. A brief discussion of several of the proposed design methods mentioned above are also included.

Detailed procedures for the design of fixed water spray barriers have been proposed. All of these methods use different approaches. The procedures have been developed from limited experimental data and may not apply in all situations, and since many factors, such as large obstructions (building, process units, other structures), and shifting wind direction will modify the dispersion characteristics of a gas cloud, an appropriate application and design must be evaluated case by case. Therefore, the following discussion merely indicates the types of procedures currently available for designing water spray systems.

McQuaid (19) developed a method using an experimental correlation whereby a water spray barrier can be sized by equating the total air entrained by a barrier (a summation of the quantity of air entrained by each nozzle) to the amount of air required to dilute the gas or vapor cloud below a certain level. The method is based on the assumption that adequate mixing requires an induced air velocity of approximately 20 feet/second. The air flow rate and the water flow rate at the nozzles are required. This method can give the type, number, and position and direction of nozzles required for a given installation. This method was derived from work carried out on the entrainment properties of water sprays used in coal mines for auxiliary ventilation. Predicted results were compared with test data on large-scale sprays as reported in the literature (19).

In contrast, Moodie (7) developed a design technique based on the assumption that a water spray barrier behaves as a jet in a crossflow. From this, a characteristic length can be defined in terms of the square root of the momentum flow rate of the barrier and a characteristic wind speed. For a specific wind speed and specified degree of dilution, the momentum flow rate can be determined from an experimental correlation. Using this information and a procedure developed by Moodie (7) for nozzle selection, the barrier can be sized in terms of its width, nozzle type, and water consumption. This method was developed from extensive test data generated using water sprays to mitigate carbon dioxide releases; therefore, it is based on substantial field data.

Apart from these proposed design methods, the only other technique that has been developed to aid in the design of fixed systems is the use of computer models to predict the performance of various spray systems (20,21,22,23). In these models, water sprays are treated as sources of momentum imparted to the air at the same location as the actual water spray. The quantity of momentum imparted is related to the flux of the air entrained by the water spray. It is assumed that the air mixes instantaneously with the gas/air mixture in the plume at the spray location, resulting in a sudden change in geometry and composition of the plume. The accuracy of such models depend on the accuracy of the dispersion model used. At best, they indicate how a spray barrier can influence the downwind development of a gas plume. However, they can help the planner decide how the dispersing effects of a water spray system can best be achieved.

Whether the system is mobile or fixed, designed as a barrier or as a fog, the following are important design characteristics:

- Water pressure,
- Water flow rate,
- Nozzle type,
- Nozzle spacing, and
- Nozzle orientation.

Research has shown that the efficiency of water spray systems increases as the water pressure increases (8,24). One source suggests that a minimum nozzle water pressure of approximately 145 psi be used for fixed systems (8), which is consistent with experience in gas-cleaning systems where scrubbing efficiency increases with energy input.

Research has also shown that the most efficient spray systems are designed so that the adjacent sprays just impinge on each other (6,24). This helps prevent the passage of the cloud between the sprays. Significant overlap is inefficient. Thus, the spacing will depend on the nozzle type, size, and spray angle selected.

Water spray systems perform as deluge type systems with all nozzles open. Based on the number of nozzles, nozzle spacing, and flow to each nozzle, up to several thousand gallons per minute of water may be required. The water supply system must be properly sized to permit operation at the designed pressure and flow rate for spray system. A municipal water system may not be able to deliver the necessary flowrate. A second water supply may be required for the spray system. Many facilities will already have this type of water system in place for fire protection. It may be appropriate to use this system to supply the spray system as well. A backup water system will often be composed of a large water storage tank that is automatically kept full. The spray system designer must decide which accidental release events are most likely to occur and whether the waste supply contains a sufficient quantity of water to mitigate these releases. In addition, drainage must be adequate to prevent flood damage.

Finally, the nozzle type and size must be chosen to provide a density of water spray at a velocity and droplet size that maximizes the dilution and/or absorption of the gas cloud. There are many basic types of nozzles; however, based on recent test data, the most useful are those producing hollow-cone and fan-tail type sprays, as illustrated in Figures 8-8 and 8-9 (6,8,24). Moodie (7) has developed a scheme where the choice of nozzle, its size, spray angle, and separation distance can be determined in a systematic fashion, based on the specific momentum flow rate for a spray.

Additional consideration must be given to the piping system when fixed systems are designed. Two general types are used: wet systems and dry systems. In a wet system, the pipes are kept full of water under pressure. In dry systems, the pipes are empty until a master valve is opened when the system is activated. If there is a danger of freezing, a dry system is required to ensure that the system is not rendered ineffective by freezing. Consideration should also be given to other hazards, such as potentially explosive processes nearby, when designing such systems.

8.3.2 Steam Curtains

Only limited information is currently available on the effective design of steam curtains. Seifert (25) has developed a mathematical model that can be used as a preliminary basis for designing such systems, and experimental evidence verifies this model (25).

The model is based on the assumption that the toxic and/or flammable gas cloud moves toward the curtain on one side while the steam jets entrain

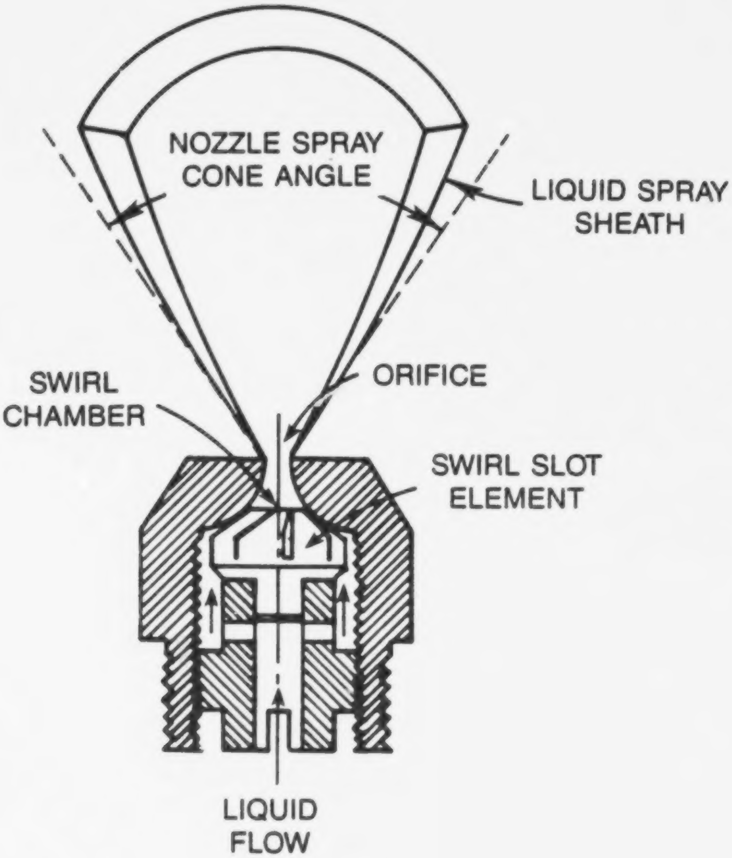
NOZZLE SPRAY
CONE ANGLE
LIQUID SPRAY
SHEATH
SWIRL
CHAMBER
ORIFICE
SWIRL SLOT
ELEMENT
LIQUID
FLOW

Figure 8-8. Typical hollow-cone spray nozzle.

Source: Adapted from Reference 26.

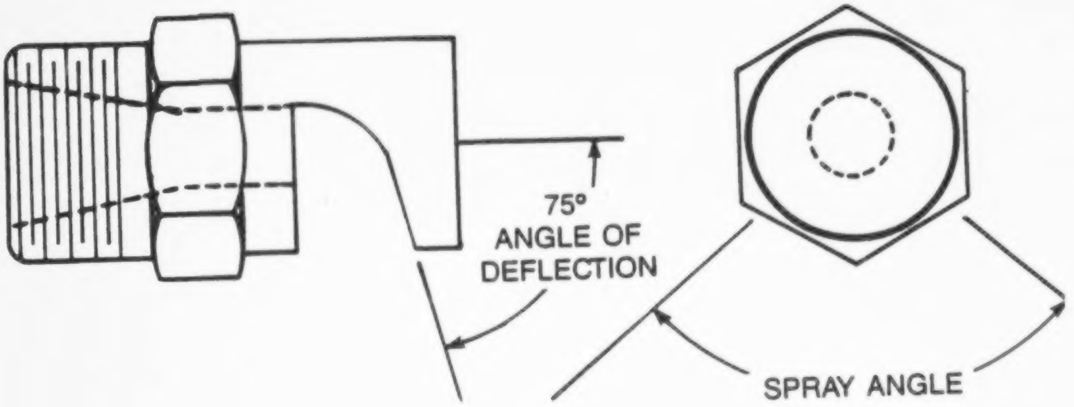
75°
ANGLE OF
DEFLECTION
SPRAY ANGLE

Figure 8-9. Typical fan-tail spray nozzle.

Source: Adapted from Reference 5.

surrounding air from the other side, as illustrated in Figure 8-10. When the released cloud reaches the curtain, the steam jets mix the gas or vapor with air and heat the vapors which provides buoyancy, causing the mixture to rise, dilute, and disperse.

The design method requires knowledge of the mass flow rate and density of the released gas or vapor. With these data, a subsequent system design can be determined for a given reduction in concentration.

8.4 APPLICABILITY AND PERFORMANCE

8.4.1 Spray Systems

Water sprays can be used to help mitigate accidental toxic and/or flammable gas or vapor releases. However, such systems are often limited in their scope and may not be capable of dealing with catastrophic releases. Although much theoretical and experimental work has been done on the use of these spray systems, the use of water spray systems is not a proven mitigation technology for all types of toxic and/or flammable gas or vapor releases.

Hazard analysis can be used to determine where a spray system might be appropriate. Such an analysis can identify the locations within a chemical facility with the highest potential for an accidental release of a hazardous vapor. The analysis can also indicate the potential impact that each release would have on the surrounding community. Sometimes there will be only a few locations within a facility with a high accidental release risk. In these situations, a fixed spray system at each potential release site may be appropriate. However, most facilities will have a number of possible release sites.

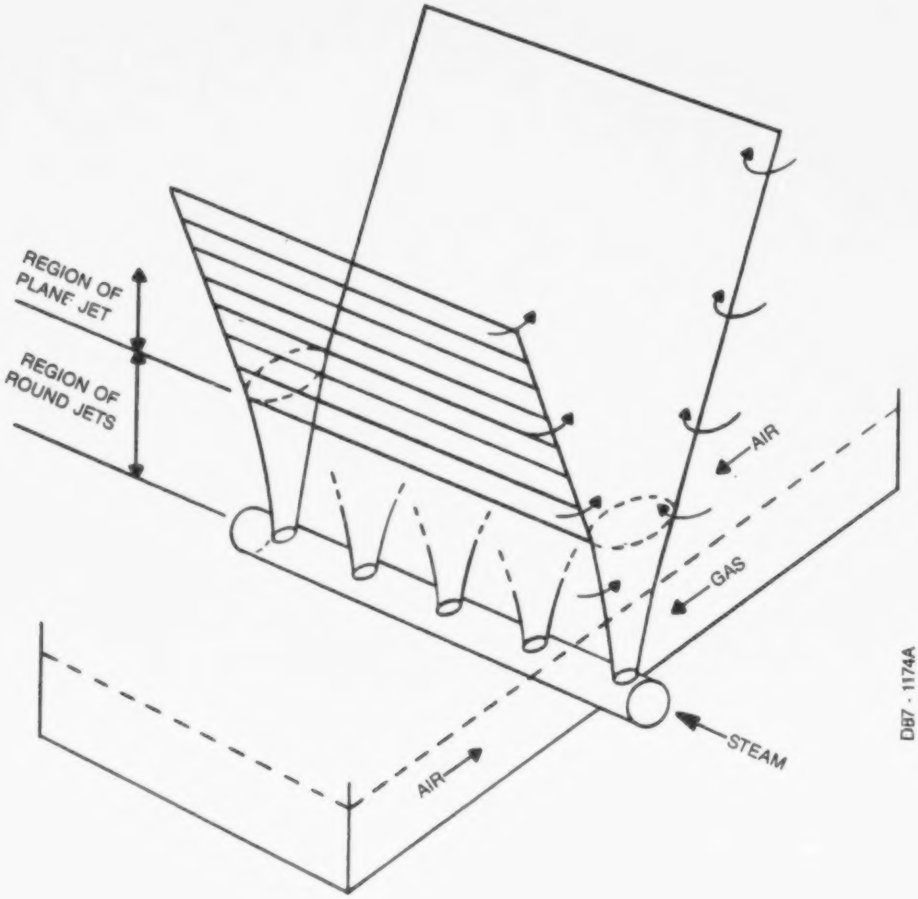
REGION OF PLANE JET
REGION OF ROUND JETS
AIR
GAS
STEAM
AIR
D87 - 1174A

Figure 8-10. Conceptual diagram of steam jets emerging from steam curtain.

Source: Adapted from Reference 25.

Since mitigative spray system technology is still in a developmental stage, there are no proven rules for designing an appropriate spray system when there are multiple release sites.

If a fixed system is installed, the potential exists that a release will occur in an area not covered by the system. Even if a release occurs in a location with a fixed spray system, the individual spray nozzles may not be directed directly at the vapor plume. The sprays from a mobile system can be directed to optimize dilution of the plume. However, a mobile system cannot be activated as quickly as a fixed system. A significant quantity of vapors can be released before the mobile system is in place.

For some facilities it may be appropriate to install fixed spray systems in the highest risk locations and have a mobile spray system on hand as a backup.

For flammable vapors, a spray system can help dilute the vapors below the flammable limit. However, the vapors can still ignite if they are present in flammable vapor phase concentrations. Mobile spray systems should only be used in situations where the personnel operating the sprays can be located away from the flammable gas cloud (this is sometimes impossible to do). A fixed spray system is safer to use for flammable vapors.

The results of the theoretical and experimental studies in recent years show that water sprays can be used effectively under certain circumstances. However, limited and often contradictory performance characteristics, optimal system design, and reliability data have been reported. Table 8-1 lists some of these studies, along with major results and performance characteristics.

Several investigations have attempted to quantify the performance of water spray systems. The most comprehensive method is that developed by Rees (6) and Moodie (7). It consists of ranking the spray system performance in

TABLE 8-1. RESULTS OF SEVERAL EXPERIMENTAL STUDIES ON THE EFFECTIVENESS OF WATER SPRAYS

Description of Study	Summary of Results	Reference
Clouds of ethylene and vinyl chloride vapor directed from ground level towards 20-foot spray barrier, with sprays directed downwards	If velocity of entrained air exceeds that of vapor cloud, spray acts as barrier. Vapor clouds with velocities of 3 and 9 mph were stopped by sprays with 100 psig nozzle pressure. Only lower velocity cloud stopped with 40 psig pressure. Where cloud passed through barrier, there was still an appreciable dilution effect. Water spray did not prevent ignition of flammable cloud and flame speed actually increased.	1 (1976)
Clouds of propane vapor directed towards spray barrier, with downward directed spray nozzles at 1, 5, 9, 15, and 20 feet above the ground, 55-feet long with nozzles 5 feet apart.	A properly designed and installed water spray system can dilute a flammable mixture below the LEL. However, the system does not act as a flame arrester. Ignition of vapor cloud depends on the spacing of nozzles and water pressure.	2 (1976)
Effectiveness of water sprays in suppressing combustion in mists of heat transfer media, specifically Dowtherm A.	Combustion suppressed by a scrubbing mechanism that reduced concentration of droplets in the mist.	3 (1976)
A water curtain generated by mobile monitors was used on a chlorine gas cloud.	The curtain successfully protected a small area against the gas cloud.	4 (1975)
A series of wide-angle, flat spray nozzles was used to disperse LNG vapors.	Two mechanisms are responsible for dilution: heating the vapor and increased turbulence. Such sprays are effective for small, confined area LNG spills. Large spills may require systems too large to be cost effective.	5 (1977)

(Continued)

TABLE 8-1. (Continued)

Description of Study	Performance Characteritics	Reference
A series of eight experiments ranging up to full scale were conducted to evaluate the performance and effectiveness of water sprays. Propane was used as gas source.	Upward water sprays are significantly more effective than downward. The best type of nozzle is a conical, narrow angle, high velocity.	6 (1981)
A series of full-scale tests using hollow-cone spray nozzles inclined downwards were conducted using carbon dioxide.	Water spray barriers can be effective in dispersing a heavy gas cloud. Nozzles pointing in a vertical direction or angled into the gas cloud at a 45° angle are most effective. Effectiveness can be optimized in terms of the water pressure.	7 (1985)
Two water spray barriers, one using downward-directed nozzles, the other using upward-directed nozzles were used to develop performance data for full-scale barriers using carbon dioxide.	High momentum discharges from flat-fan nozzles with spray angles of 90° or less are most effective. At a wind speed of 5 mph, a vertical system can produce a ratio of gas concentration with and without sprays of approximately 4. At a wind speed of 20 mph, this ratio decreased to about 1.5.	8 (1981)

terms of a concentration reduction (CR) ratio (Moodie (7)) or a forced dispersion (FD) factor (Rees (6)); both are a ratio of gas concentrations with and without a water spray observed at a point downstream.

Moodie (7) demonstrated that, in general, high momentum discharges from flat-fan spray nozzles with spray angles of 90° or less are the most effective. Experimental results using carbon dioxide indicated that at a wind speed of 5 mph, a properly designed vertical water spray system directed upwards produced a CR ratio of approximately 4. At a wind speed of 20 mph, the effectiveness was reduced to 1.5.

Prugh (27) developed a systematic method in which the maximum theoretical effectiveness of a water spray barrier can be calculated. Material balances are used to determine the mole-fraction of vapor in the air exiting the barrier, which is then compared with the average crosswind concentrations of the vapor in the air entering the barrier, resulting in a reduction factor for the system. However, this method is limited to water-soluble vapors.

In general, water sprays can be an effective means of absorbing water-soluble gas or vapors (e.g., ammonia). However, for many released chemicals the efficiency of absorption may be low because of mass transfer limitations. As a result, a second water spray barrier may also be required further downstream.

Likewise, water spray barriers appear to be limited in their effectiveness. It has been reported that these barriers are only marginally effective in reducing the hazards of gases and vapors not soluble in water (3,19,21,28,29,30). Others have gone as far as regarding them as being limited to water-soluble, low-density, and/or non-flammable vapors (7).

8.4.2 Steam Curtains

Steam curtains were initially designed to dilute and contain heavy flammable vapors and are incorporated into several installations to prevent highly flammable materials from reaching sources of ignition in the event of an accidental release (17,18,31). In principle, steam curtains can also be helpful in mitigating heaver-than-air releases of toxic and/or flammable vapors. At the time this manual was prepared, no commercial steam curtain installations were known to exist for mitigating toxic releases.

In general, the characteristics of water spray systems described in Section 4 are similar to those of steam curtains. However, steam curtains require large quantities of steam, typically 0.15 ton/hr per foot of curtain. Therefore, they must often be limited to small-scale uses. Also, where steam is not available or where the supply of steam is not reliable, water spray systems may be more applicable.

The effectiveness of steam curtains has been investigated experimentally by Rees (32), Seifert (26), and Rulkens (33). These investigations found that steam curtains can reduce the concentration of a vapor cloud from an accidental release. Table 8-2 shows the effectiveness of steam curtains for diluting a flammable gas to levels below its lower flammability limit (9). The primary advantage of steam curtains over water sprays is that steam curtains enhance the buoyancy behavior of the cloud by heating the vapors reaching the curtain.

However, steam curtains are reported to be less effective at mixing than water sprays at the same supply pressure (32). More steam is required for comparable mixing. This can be more important for toxic than flammable vapors or gases since the former are hazardous at lower concentrations. The buoyancy effect may still be beneficial, however. For example, for materials like ammonia, whose density is near that of air, heating from the steam curtain may

TABLE 8-2. EFFECTIVENESS OF STEAM CURTAINS[a]

Source Strength[b] (lb/s)		44			132			264		
Wind Velocity (ft/s)		3.3	6.6	13.2	3.3	6.6	13.2	3.3	6.6	13.2
Distance from Curtain to Source (ft)	Steam Flow (ton/hr)									
165	25	+	-	0	+	-	-	-	-	-
	50	+	+	0	+	-	-	+	-	-
	100	+	+	0	+	+	-	+	+	-
330	25	+	+	0	+	-	0	-	-	-
	50	+	+	0	+	+	0	+	-	-
	100	+	+	0	+	+	0	+	+	-
500	25	+	0	0	+	-	0	+	-	0
	50	+	0	0	+	+	0	+	+	0
	100	+	0	0	+	+	0	+	+	0

Note:
+ effective
- not effective
0 sufficient dilution by wind alone

[a] Based on propylene release diluted below 2 percent.
[b] Amount of propylene released at the source.

Source: Adapted from Reference 9.

be sufficient to cause the plume to become buoyant and airborne, which would result in a significant reduction in downwind ground level concentrations.

8.5 RELIABILITY

8.5.1 Spray Systems

Reliability data for water spray release mitigation systems do not appear to be readily available. In general, the reliability of water spray systems should depend on the design of the system and on the reliability of the individual components that make up the system. However, reliability is more than the degree to which a piece of hardware is free of basic defects that may prevent it from operating properly. It also includes human factors, interactions, and controls that determine whether a systems is effective or not.

System unreliability can often result from events other than simple mechanical failure, including:

- Failure to properly define the hazard;
- Inadequate quality control;
- Poor maintenance;
- Incorrect operations of the system; and
- Changes made to the surrounding systems that were not accounted for in the original spray system design.

Systems must be regularly inspected and maintained. Of particular importance are the spray nozzles, which must be inspected and cleaned as necessary, or provided with some type of nozzle protection to ensure that their small water passages remain clear.

8.5.2 Steam Curtains

A steam curtain system can be no more reliable than the steam source. Steam pressure must be available. Since the system is dormant much of the time, the mechanism that activates it could become inoperable if neglected. Reliability depends on regular inspection, testing, and maintenance.

8.6 SECONDARY HAZARDS

8.6.1 Spray Systems

Water spray systems pose some potential hazards if they are used in certain circumstances. This subsection briefly discusses some of the potential hazards.

For some materials (e.g., hydrogen chloride, hydrogen fluoride, and chlorine), applying water directly at the leakage point will result in an acceleration of the corrosive effect of the chemical. This can result in an enlarged release hole and an increase in the rate of release. Similarly, spraying water on a spill of liquified gas such as chlorine would add heat to the subcooled pool of liquified gas, resulting in increased vaporization.

For some chemicals, water sprays can lead to the formation of highly toxic, acidic, or alkaline liquid droplets that may be hazardous or potentially more hazardous than the original release.

Finally, where mobile systems are used, personnel can be injured if appropriate protective clothing and breathing apparatus are not worn.

8.6.2 Steam Curtains

Steam curtains, particularly those with jets containing wet steam, can create static electricity. The generation of static electricity in steam curtains has been investigated by several individuals (26,33). Static electricity could ignite a flammable vapor or gas. Static discharges from steam jets can be prevented by grounding all pipework and other metal in contact with the steam.

Additional secondary hazards are similar to those presented for spray systems.

8.7 COSTS

8.7.1 Spray Systems

The cost of a water spray system depends on the type of system used (i.e., fixed or mobile) and will be similar to costs for fire protection systems and equipment. Table 8-3 lists the costs of typical components for both a fixed and a mobile system. Design bases for these costs are presented in Table 8-4.

For fixed systems, the major portion of the actual system cost is that associated with the piping and water supply system. If an existing supply of water for fire protection systems can also be used for mitigation purposes, the only major additional cost is that of the extra pipework and nozzles needed for the water spray system. These systems may, however, be limited in their application size. Thus, for very large installations, mobile systems may be more cost-effective.

TABLE 8-3. TYPICAL COSTS ASSOCIATED WITH FIXED AND MOBILE WATER SPRAY SYSTEMS

Item	Capital Cost Range (1987 $)	Annual Cost Range (1987 $/yr)
Mobile Water Spray System:		
Fire Hose	4 - 5 per linear foot	0.35 - 0.90 per linear foot
Fog Nozzle	250 - 300	20 - 25
Fire Hydrant	400 - 500	35 - 45
Fire Monitor	750 - 1,000	65 - 85
Fixed Water Spray System:		
Deluge type, water spray system	300 - 350 per nozzle	25 - 30 per nozzle
Spray nozzle	60 - 80	5 - 7
Deluge valve	1,400 - 1,500	120 - 130
Fire pump	25,000 - 30,000	2,100 - 2,600

Source: See Table 8-4 for references.

TABLE 8-4. EQUIPMENT SPECIFICATIONS FOR MOBILE AND FIXED WATER SPRAY SYSTEMS USED IN COST ESTIMATES

Item	Specification	Reference
Mobile Systems:		
Fire Hose	High strength, 500 lb. test, 2-1/2 in. diameter.	36
Fog Nozzle	Adjustable nozzle, 1-in. booster inlet	36
Fire Hydrant	Standard 4-in. hydrant with two 2-1/2 in. hose connections.	36,37
Fire Monitor	Standard fire monitor with adjustable nozzle, 500 gpm capacity.	36,37
Fixed Systems:		
Water Spray System	Deluge type, fixed-pipe system capable of delivering 3,000 gpm of water to source. Includes piping and supports.	38,39
Spray Nozzle	Fan-tail or hollow-cone type, carbon steel construction.	36
Deluge Valve	2-inch deluge valve, including trim, pressure-operated relief, emergency release, and pressure gauge.	36
Fire Pump	5-inch centrifugal pump, 99 hp, 100 psi, 1,000 gpm, diesel operated.	36

8.7.2 Steam Curtain

The costs of typical components associated with steam curtain systems are shown in Table 8-5. Since there are many individual variations of components, the system chosen is for illustrative purposes only. These costs provide an order-of-magnitude basis for estimating the total cost of a steam curtain system.

TABLE 8-5. ESTIMATED COSTS FOR A TYPICAL STEAM CURTAIN SYSTEM[a]

	Capital Cost (1987 $)	Annual Cost (1987 $/yr)	References
Piping	7,000	1,200	30
Concrete wall	2,500	220	39
Globe valve	1,000	90	40
Remote shutoff valve	3,000	450	40
Steam supply[b]	$4.50/hr	$68/hr	40

[a] Basis: 6-inch Schedule 40 carbon steel piping, 100 feet long with 3/16-inch holes, 1 foot apart
250 psig steam supply
Concrete walls, 4 feet high, 100 feet long, 6 inches thick.

[b] Based on a steam requirement of 0.15 ton/hr per foot of curtain and a steam cost of $15 per 1000 pounds.

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SECTION 9
FOAM SYSTEMS

Foams, which are used in the chemical process industries to control and extinguish certain types of hydrocarbon fires involving spilled liquids, are used when the fire may not be effectively controlled by water spray application. Although originally developed for firefighting purposes, some of the same properties that make foams effective for controlling fires also make them useful for controlling the release of vapors from volatile chemical spills. The application of a foam blanket to a liquid spill may prevent the release of a flammable gas or vapor from reaching an ignition source in concentrations that could result in an explosion or fire. In the case of a nonflammable toxic liquid spill, foam may help prevent personnel or general public exposure to dangerous concentrations of a hazardous gas or vapor being emitted from the surface of the liquid.

This section of the manual discusses the use of firefighting and specialty foams to control vapor hazards from spilled volatile flammable and/or toxic chemicals. The different types of foams and basic design considerations are described, as well as their applicability, performance capabilities, and reliability. Secondary hazards that may limit the use of foams for controlling vapor hazards from certain hazardous liquid spills are also described.

9.1 BACKGROUND

Foams used for firefighting consist of a mass of gas-filled bubbles which, when applied to a liquid hydrocarbon fire, control and extinguish the flames. The properties of foam that make it effective for fighting fires are (1,2):

- Ability to blanket the spilled liquid surface with a material that has a lower density than the liquid, thereby extinguishing an existing fire by cutting off the source of combustion air;

- Suppression of potentially flammable vapors from being emitted to the atmosphere and mixing with combustion-supporting air;

- Prevention of nearby flames from heating the spilled liquid covered by the foams; and

- Cooling of the spilled liquid with water draining from the foam and surrounding surfaces to help prevent reignition.

These properties are also helpful in mitigating the release of flammable and/or toxic vapors before actual ignition or exposure of personnel.

Two varieties of foams, chemical and mechanical, are used for firefighting. Chemical foam is produced by a chemical reaction, such as the reaction that occurs when an aqueous solution of sodium bicarbonate is mixed with aluminum sulfate and sulfuric acid (3,4). With the addition of other chemicals acting as foam stabilizers, the reaction produces a foam consisting of carbon dioxide-filled bubbles (1). Originally introduced to control coal fires in the 19th century (2), chemical foam has been largely replaced by mechanical foam, which consists of air-filled bubbles (2,3). This "air" foam is produced by mechanical aeration of a mixture of foam concentrate and water using a foam-making device. Mechanical foams developed for fire control include regular protein foam, fluoroprotein foam, surfactant foam, aqueous film-forming foam (AFFF), and alcohol-type foam (ATF) (5). A discussion of each of these conventional firefighting foams and other special foams developed specifically to control vapors is included in Subsection 9.2. The various types of equipment used to generate and apply these foams to spills are also described in Subsection 9.2.

An important quality of firefighting foam is the expansion ratio, which is the ratio of the volume of foam produced to the volume of solution fed to the foam-making device. Foams are classified as low-, medium-, and high-expansion foams (6). Low-expansion foams have expansion ratios of from 2:1 to 15:1. Medium-expansion foams have expansion ratios from 15:1 to 100:1, while high-expansion foams are those with expansion ratios of from 100:1 to 1000:1. While these particular ranges of expansion ratios have been presented in the literature for firefighting foams (6), the ranges are rather subjective and can be different for the low-, medium-, and high-expansion foams used for vapor control. These different range are discussed in Subsection 9.2.

Most firefighting foams, including regular protein, fluoroprotein, aqueous film-forming foam (AFFF), and alcohol-type foam (ATF), are available in 3 percent and 6 percent concentrations. This percent value indicates the amount of foam concentrate that should be mixed with water to form the foam solution, which is then aerated to create the actual foam. For example, to produce 100 gallons of foam solution, 3 gallons of 3 percent foam concentrate would be mixed with 97 gallons of water (1). If the particular foam had an expansion ratio of 10:1, 1000 gallons of foam could be produced for application to the fire or spill.

Other important qualities of firefighting foams are fluidity and drainage rate (4). The foam should flow easily around obstructions in the spill area and quickly cover the liquid surface without breaking up the flame smothering "blanket." A good firefighting foam possesses a shear stress value of 150 to 250 dynes/cm^2, as measured on a torsional vane viscometer (4). The drainage rate of a foam is a critical property for firefighting, as well as for vapor control, as discussed in Subsection 9.2. The drainage rate is referred to as the "25 percent" or "quarter drainage time." The "quarter drainage time" is the time, in minutes, it takes for a foam to loose 25 percent of the liquid used to make the foam. For a good firefighting foam, the drainage rate is 2 to 5 minutes (4).

9.2 DESCRIPTION

The ability of foams to mitigate vapor released from volatile liquid chemical spills has grown out of their ability to extinguish fires and prevent reignition by isolating the spilled material and volatile vapors from ignition sources. The foam blanket insulates the liquid from ignition sources and radiant heat sources that cause vaporization. The foam acts as a physical barrier, because of its limited permeability, and suppresses vapor loss to the atmosphere. The foam may also absorb vapors being emitted from the spill surface (3,7). For refrigerated liquid spills, the foam can help warm the emitted vapor, which passes through the applied foam layer, thus allowing the vapors to rise and disperse (8). Foams can also provide water for diluting certain water-reactive chemical spills (3). On the other hand, the accelerated boil-off of regrigerated liquids or violent reactions with water-reactive chemical spills can occur. These secondary hazards are discussed in more detail in Subsection 9.6.

The effectiveness of a foam depends on the type of chemical spilled, the type of foam selected to control the spill, the general qualities of foam that help control the release of vapors, and foam generation equipment.

9.2.1 Types of Foams

Six types of foams are used to control vapors from chemical spills: regular protein foams, fluoroprotein foams, surfactant foams, aqueous film-forming foams (AFFF), alcohol-type (ATF) or polar solvent foams, and special foams (9). The first five were developed for firefighting, while the special foams have been developed specifically to control vapor releases from spills.

Regular Protein Foams--

Protein foams, derived from hydrolyzed protein, are the oldest of the mechanical firefighting foams. The use of protein foam in controlling vapor release grew out of its use as an extinguishing agent for aromatic hydrocarbon fuel fires and its effectiveness in preventing the emission of ignitable vapors. Some of the important characteristics of regular protein foam are listed below (2,3,6,10):

- Demonstrated spill control capability for water-immiscible, non-polar hydrocarbon fuels such as petroleum products, gasoline, fuel oil, jet fuel, etc.;
- Designed for low expansion foam-making equipment;
- Desirable physical characteristics (good adhesion, stability, water retention, elasticity, and mechanical strength);
- Good heat resistance, resistance to burnback (burning back of the foam blanket if the blanket is broken) and resistance to reignition;
- Non-toxic and biodegradable after dilution;
- Among standard types of foam in use by fire service departments;
- Fresh or sea water can be used to make foam solution;
- Limited shelf life for foam concentrates;
- Poorer flowing ability and slower fire knockdown ability than other foam types; and
- Can be used in temperature range of 20°F to 120°F.

Fluoroprotein Foams--

Fluoroprotein foams are similar to regular protein foams, but also contain fluorinated surfactants, which allow the foam to shed fuel from its surface if the foam becomes coated with hydrocarbon material (3,10). This fuel-shedding characteristic is important when fighting hydrocarbon tank fires or in cases where the foam is injected below the surface of the fuel fire (10). With the following exceptions, the characteristics of fluoroprotein foams are similar to those of regular protein foam. These exceptions are noted below (2,10):

- Better suppression of hydrocarbon fuel vapors than regular protein and AFFF foam;
- Better resistance to burnback than protein foam;
- Better compatability than regular protein foam with dry chemical agents; and
- Faster fire knockdown ability than regular protein foam, but slower than AFFF foam.

Surfactant Foams--

Surfactant foams are produced for application as low-, medium-, and high-expansion foams from detergent foam concentrates. These concentrates consist of synthetic hydrocarbon surfactants (syndets) (10). Some important characteristics of surfactant foams are shown below (3,10):

- Applicable to water-immiscible, non-polar hydrocarbons;
- Resistance to burnback and fire knockdown ability is not as good as that of other low-expansion foams;
- Capability of expansion ratios of up to 1000:1 for total flooding capability;
- Readily available surfactant foams are mostly anionic;
- Non-toxic and biodegradable;

- Unlimited shelf life if stored properly;
- Produce less odor when burned than do other foam types;
- Large variety of concentrates on market, with wide range of physical properties, which can make proper selection difficult; and
- Available in concentrates to yield from 1 to 6 percent foam solutions;

Aqueous Film Forming Foams (AFFF)--

Concentrations for AFFF foams are composed of fluorinated surfactants and hydrocarbon surfactants for fast knockdown of water-immiscible, non-polar hydrocarbon fuel fires. Additional characteristics of AFFF foam are listed below (2,3,6,10):

- Ability to be used in low- to high-expansion foam-making equipment;
- Ability to spread a water solution film across spill quickly to extinguish fire, exclude combustion air, and stop fuel from vaporizing or toxic vapors from being emitted;
- Water of composition lost more quickly after application than with other foams;
- Low viscosity;
- Available in concentrates to yield 3 and 6 percent foam solutions;
- Fresh or sea water can be used to make foam solution;
- Non-toxic and biodegradable after dilution; and
- Long shelf life.

Alcohol-Type Foam (ATF)--

Alcohol-type foam was developed to use on fires involving water-miscible, polar materials, where ordinary air foams exhibit rapid breakdown and loss of effectiveness. Examples of polar materials for which ATF foams have been used are alcohols, paint thinners, methyl ethyl ketone, acetone, isopropyl ether, acrylonitrile, ethyl and butyl acetate, and amines and anhydrides (10). ATF foams consist of a regular protein, fluoroprotein, surfactant, or AFFF concentrate with additives of a metal stearate or a polar material resistant polymer (2,3,6,10). ATF foams using polymers resistant to polar materials are applicable to both non-polar hydrocarbon and polar solvents. When these types of "universal" foams are applied to a spill, a gel is formed on the surface. This gel forms an insoluble, low-permeability polymeric layer between the foam and the spilled chemical that protects the film and foam from degradation, and mitigates the release of vapor from the spill. ATF foams are generally available in concentrations to yield 3 and 6 percent foam solutions. These foams are normally used at temperatures of from 35°F to 120°F.

Special Foams--

Special foams are those developed to suppress hazardous vapors from liquid spills that typical firefighting foams cannot control effectively. Examples[a] of these are Hazmat NF® Number 1 and Hazmat NF® Number 2 produced by National Foam, and Type V foam (VEE foam®) by MSA Research (11). Hazmat NF® Number 1 is designated to use on spills involving alkaline materials, while Hazmat NF® Number 2 is for acid material spills. MSAR Type V foam is for controlling hazardous vapors from water-reactive chemicals.

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[a] These products are mentioned as examples only; such mention does not constitute an endorsement.

9.2.2 Foam Quality

Two important qualities of a foam will effect its ability to control vapors from hazardous volatile chemical spills: the expansion ratio and the quarter drainage time. The quarter drainage time is a measure of the stability of the foam. More stable foams can prevent vapor from being emitted from the spill for longer periods of time than can less stable foams.

As indicated in Subsection 9.1, expansion ratio classifications are somewhat subjective and there is no definite agreement on what constitutes a low-, medium-, or high-expansion ratio foam. Ratios can range from less than 20:1 to over 150:1. High-expansion foams have long quarter drainage times, sometimes greater than one hour, but can be blown away by the wind, while medium-expansion foams and low-expansion foams have quarter drainage times of between approximately 15 and 30 minutes, and between 3 and 12 minutes, respectively.

Medium-expansion foams may be the most effective for controlling vapors from spilled volatile materials. They can be applied more easily than high-expansion foams and will not be blown away as easily by wind. They also exhibit longer quarter drainage times than do low-expansion foams, and thus require less frequent reapplication.

9.2.3 Foam Application Systems

Foam systems consist of a stored quantity of foam concentrate, a water supply to mix with the concentrate and a nozzle system to introduce air into the foam solution to produce the expanded foam for application to the spill. Foam systems may be fixed, semifixed, or portable (6).

the foam solution to produce the expanded foam for application to the spill. Foam systems may be fixed, semifixed, or portable (6).

Regardless of the type of foam system selected, a proportioning system or proportioner is used to mix the foam concentrate with the make-up water to form the foam solution. The expanded foam is generated by mechanically mixing air with the foam solution within a nozzle. The specific types of equipment used to make the foam depends on the type of foam and the expansion ratio. Low- and medium-expansion foams can be generated using various foam types and nozzles. Examples of portable air aspirating foam-making equipment typically used to respond to hazardous chemical spills are described in References 3 and 10. Generally, foam application systems are sold as part of a total package from the foam vendors, and design of a custom system is not necessary.

9.3 DESIGN

The design of a foam system depends primarily on the type of hazard involved. In the case of a volatile chemical spill, an appropriate foam concentrate should be selected and on hand to control the release of hazardous vapors from that particular material. For handling emergency releases in chemical processing plants, the user needs to review the types of hazardous chemicals and the potential areas for spill releases in order to select the proper speciality foam and equipment. In the case of a transportation accident and subsequent chemical release, fire service departments may have a limited selection of foams to choose from, which may or may not be appropriate in controlling vapor releases from the spill. A table showing the qualitative performance abilities of various foams on several chemicals is shown in Subsection 9.5.

If the type of hazard and foam to control this hazard have been defined, the other major design criteria are:

- The water supply; and
- The magnitude of the hazard.

Without an adequate supply of water at the required rate and pressure, the foam application system may be inoperable or unable to produce the necessary quantity of foam to control the release (6).

The potential size of the chemical spill is also an important design criterion. If the size of a spill, for instance within a diked area, can be determined before a release, the amount of water at adequate pressure and flow rate can be planned for, along with the amount of foam concentrate that would fully contain the release.

For contained and uncontained chemical spills, the size of the hazard influences the selection of application equipment and methods, and suitable foams of the appropriate quality for controlling vapors from the spill. These are discussed below.

9.3.1 Application Equipment and Methods for Low-/Medium-Expansion Foams

Air-aspirating foam nozzles for applying low- and medium-expansion foams should be selected that minimize the drainage of liquid from the foam and allow maximum expansion. These include turret-mounted or hand-held nozzles that disperse the foam as a stream or spray; however, use of fog-foam nozzles can effectively reduce the expansion ability of the foam. Different nozzles may produce foam of varying quality; therefore, it is important to choose the nozzle that yields the desired quarter drainage time and expansion ratio with a given foam. Detailed discussions with foam and equipment manufacturers or tests may be required to evaluate equipment and the actual quality of the foam as applied.

Low-expansion foams should be applied in such a way that the foam is not sprayed directly into the spill. The foam stream or spray should be directed just in front of the spill and allowed to flow into the spill area or directed onto a wall or other surface just behind the spill (7,9). This allows the foam to blanket the surface with minimal disturbance of the spilled chemical.

The selection of application equipment and the foam application rate can be determined from the desired foam depth, the area of the spill, the time required to achieve complete blanketing of the spill, and the expansion ratio of the foam, as given by the formula shown below:

$$R = \frac{7.48\ DA}{TE}$$

Where:

R = Discharge capacity of foam solution for nozzles (U.S. gal/min)
D = Depth of foam (ft)
A = Spill area (ft^2)
T = Time required to completely blanket spill (min)
7.48 = conversion factor (U.S. gal/ft^3)
E = Expansion ratio of foam

For a 5000-square-foot spill to be covered by a 0.5 foot thick foam blanket within five minutes, about 190 gallons per minute of foam solution with an expansion ratio of 20:1 would be needed. This may require the use of several smaller nozzles (i.e., 3-60 gallons per minute nozzles) or fewer larger flow rate nozzles. For 60 minutes of operation using a foam concentrate that yields a 6 percent foam solution, approximately 690 gallons (190 gal/min x 60 min x 0.06) of foam concentrate would be required to control the spill.

9.3.2 Application Equipment and Methods for High-Expansion Foams

High-expansion foams are applied to a chemical spill by means of a foam chute. They are used indoors to totally flood an area to extinguish fires. Use of these foams outdoors to control vapor releases from spills is limited to situations where the wind speed is less than 10 miles per hour, unless precautions are taken to restrain displacement of the foam by the wind.

The application rate for the generated foam should exceed 0.5 cubic feet per minute per square foot of spill area. Foams should be applied to flammable liquids to a thickness of at least 18 inches.

9.4 APPLICABILITY AND PERFORMANCE

Certain types of aqueous foams have been shown to be effective in controlling the release of flammable and/or toxic vapors from various chemical spills. A major criterion in selecting a foam is the compatibility of the foam with the spilled chemical. Foams have limited effectiveness in controlling vapor releases from flowing spills. To control vapor releases, the spill must first be physically contained.

Currently, it does not appear that foams are used to control airborne releases of hazardous chemicals; however, foams have been used for gas scrubbing (8). Some work has been done where a contaminated air stream has been sent into a foam generation machine, where the air is incorporated into the foam. The contaminant is then temporarily trapped in the foam, where its rate of release is slowed, or where it is absorbed by the water in the foam. Such a system could be used wherever the vapors from an accidental release could be contained and routed into the foam-generation machine. In such situations, however, an alternate treatment system such as a scrubber or flare could also be used.

The use of aqueous foams for controlling vapors from water-immiscible hydrocarbon fuels is well established because of their use in extinguishing fires. The use of typical commercial fire-fighting foams is limited to non-polar materials with dielectric constants of less than three; otherwise, rapid degradation of the foam will occur (3). For control of water-miscible, polar material spills, alcohol-type foams (ATF) have been developed that protect the foam blanket by creating a film barrier between the spilled material and the foam. Universal or multipurpose foam agents have also been produced that are effective against both polar and non-polar solvents, and chemically neutral material spills (7). Specialty foams have been developed to control hazardous vapor releases from spills of alkaline-, acid-, and water-reactive chemicals.

Another major point in foam selection is the drainage of liquid from the foam, or the quarter drainage time. The longer the quarter drainage time, or the longer the foam retains its water, the better its fluidity, spreading capability, collapse resistance, and heat resistance (in the case of fire) (11).

Because of the variety of fire-fighting and specialty foams available and the numerous chemicals in commercial use, it is important to evaluate which foams are applicable for controlling vapor from spills of particular chemicals. Table 9-1 shows an overview of the types of foam which are useful for controlling vapors from spills of specific chemicals. Shown in this table are the chemical group, the particular chemical, the recommended type of foam, satisfactory types of foam, and ineffective or dangerous types of foams. New foams for vapor control will probably be developed for these and other chemicals. Therefore, foam manufacturers should be consulted before selecting foam concentrates, particularly for chemicals not listed in Table 9-1. Table 9-2 shows typical application information about some universal and specialty foams available from some manufacturers.

Depending on the type of foam used and the material spilled, foams can reduce vapor concentrations, measured just above the foam layer, by over 90 percent (8). However, this reduction is temporary and eventually the vapor concentration above the applied foam layer will reach its uncontrolled concentration as the foam breaks down over time. The length of time that a foam can effectively mitigate vapors without reapplication can range from 5 to 120 minutes (8). An illustration of the mitigation of vapor released from liquid benzene is illustrated in Figure 9-1 (3).

TABLE 9-1. FOAMS FOR CONTROL OF FLAMMABLE/TOXIC VAPORS

Group	Chemical	Recommended Foam Types (Minimum Thickness/ Reapplication Rate)(in/min)[a]	Satisfactory Foam Types (Minimum Thickness/ Reapplication Rate)(in/min)[a]	Ineffective/Dangerous Foam Types (Reason)
ALCOHOLS	Butanol, methanol, and propanol	Alcohol (ND)[b]	None	AFFF (collapse) Fluoroprotein (collapse) Protein (collapse) Surfactant H&L[c] (collapse)
	Octanol	Alcohol (ND)	AFFF Fluoroprotein Protein Surfactant H&L	
ALDEHYDES AND KETONES	Acetone, methyl ethyl and methyl butyl ketones	Alcohol (10/60)	None	AFFF (collapse) Fluoroprotein (collapse) Protein (collapse) Surfactant H&L (collapse)
AMINES	Ethylamines, ethylene diamine, hydrazine, and methylamines	Alcohol (ND) Hazmat NF #1 (ND)[d] MSA Type V (ND)	None	AFFF (collapse) Fluoroprotein (early breakthrough) Protein (collapse) Surfactant H&L (collapse)

(Continued)

TABLE 9-1. (Continued)

Group	Chemical	Recommended Foam Types (Minimum Thickness/ Reapplication Rate)(in/min)[a]	Satisfactory Foam Types (Minimum Thickness/ Reapplication Rate)(in/min)[a]	Ineffective/Dangerous Foam Types (Reason)
ETHERS	Ethyl ether	Alcohol (5/25-120)	None	AFFF (collapse) Fluoroprotein (collapse) Protein (collapse) Surfactant (collapse)
ESTERS	n-Butyl acetate	AFFF (5/120) Alcohol (5/120) Fluoroprotein (5/120) Protein (5/120) Surfactant L (5/120)	None	Surfactant H (no information)
	Methyl acrylate	Alcohol (ND)	None	AFFF (collapse) Fluoroprotein (collapse) Protein (collapse) Surfactant H&L (untested)
	Vinyl acetate (monomer)	Alcohol (ND) Fluoroprotein (ND)	AFFF (ND)	Protein Surfactant H&L
HYDRO-CARBONS (ALI-PHATIC)	Ethane and ethylene	Surfactant H (ND)	Alcohol (ND) Fluoroprotein (ND) Protein (ND) Surfactant L (ND)	AFFF (accelerates boil-off)

(Continued)

TABLE 9-1. (Continued)

Group	Chemical	Recommended Foam Types (Minimum Thickness/ Reapplication Rate)(in/min)[a]	Satisfactory Foam Types (Minimum Thickness/ Reapplication Rate)(in/min)[a]	Ineffective/Dangerous Foam Types (Reason)
HYDRO-CARBONS (ALI-PHATIC) (con't)	Heptane	Alcohol (ND) Fluoroprotein (ND) Protein (ND) Surfactant H&L (ND)	AFFF (ND)	None
	Hexane and octane	Alcohol	AFFF Fluoroprotein Protein Surfactant	None
HYDRO-CARBONS (AROMATIC)	Benzene	Alcohol (2.5/120)	Fluoroprotein (5/60) Protein (5/60) Surfactant H (25/50)	AFFF (early break-through) Surfactant L (early breakthrough)
	Ethylbenzene	AFFF (5/120) Alcohol (5/120) Fluoroprotein (5/120) Protein (5/120) Surfactant L (5/120)	Surfactant H (50/30)	None

(Continued)

TABLE 9-1. (Continued)

Group	Chemical	Recommended Foam Types (Minimum Thickness/ Reapplication Rate)(in/min)[a]	Satisfactory Foam Types (Minimum Thickness/ Reapplication Rate)(in/min)[a]	Ineffective/Dangerous Foam Types (Reason)
HYDRO-CARBONS (AROMATICS) (Con't)	Toluene	Alcohol (ND) Fluoroprotein (ND) Protein (ND)	AFFF (5/40) Surfactant H (50/30) Surfactant L (5/30)	None
HYDRO-CARBONS (ALI-CYCLIC)	Cyclohexane	Alcohol (5/>120) Fluoroprotein (5/>120) Protein (5/>120)	AFFF (5/60) Surfactant H (ND) Surfactant L (5/30)	None
HYDRO-CARBONS (INDUS-TRIAL	Gasoline and kerosene	Alcohol (ND) Fluoroprotein (ND) Protein (ND) Surfactants (ND)	AFFF (ND)	None
	Naphtha	Alcohol (ND) Fluoroprotein (ND) Protein (ND)	AFFF (ND) Surfactants (ND)	None
LIQUEFIED ORGANIC GASES	Ethylene oxide	None	Alcohol (ND)	AFFF (collapse) Protein (collapse) Fluoroprotein Surfactant H (untested)

(Continued)

TABLE 9-1. (Continued)

Group	Chemical	Recommended Foam Types (Minimum Thickness/ Reapplication Rate)(in/min)[a]	Satisfactory Foam Types (Minimum Thickness/ Reapplication Rate)(in/min)[a]	Ineffective/Dangerous Foam Types (Reason)
LIQUIFIED ORGANIC GASES (con't)	Liquefied natural gas	Surfactant H (ND)	None	AFFF (early breakthrough) Alcohol (early breakthrough) Fluoroprotein (early breakthrough) Protein (early breakthrough) Surfactant L (early breakthrough)
INORGANICS	Carbon disulfide	Hazmat NF #2 (ND) MSA Type V (ND)	None	AFFF (untested) Alcohol (untested) Fluoroprotein (untested) Protein (early breakthrough) Surfactant H&L (untested)
	Hydrochloric acid and hydrogen chloride (anhydrous)	Hazmat NF #2 (ND) MSA Type (V (ND)	None	AFFF (untested) Alcohol (untested) Fluoroprotein (untested) Protein (untested) Surfactant H&L (untested)

(Continued)

TABLE 9-1. (Continued)

Group	Chemical	Recommended Foam Types (Minimum Thickness/ Reapplication Rate)(in/min)[a]	Satisfactory Foam Types (Minimum Thickness/ Reapplication Rate)(in/min)[a]	Ineffective/Dangerous Foam Types (Reason)
INORGANICS (con't)	Nitric acid	Hazmat NF #2 (ND) MSA Type V (ND)	None	AFFF (untested) Alcohol (untested) Fluoroprotein (untested) Surfactant H&L (untested)
	Silicon tetrachloride	Surfactant H (ND)	None	AFFF (violent reaction) Alcohol (violent reaction) Fluoroprotein (violent reaction) Protein (violent reaction) Surfactant L (violent reaction)
	Sulfur trioxide	Hazmat NF #2 (ND) Surfactant H (ND) MSA Type V (ND)	None	AFFF (violent reaction) Alcohol (violent reaction) Fluoroprotein (violent reaction) Protein (violent reaction) Surfactant L (violent reaction)
	Titanium tetrachloride	Hazmat NF #2 (ND) MSA Type V (ND)	None	AFFF (untested) Alcohol (untested) Fluoroprotein (untested) Protein (untested) Surfactant H&L (untested)

(Continued)

TABLE 9-1. (Continued)

Group	Chemical	Recommended Foam Types (Minimum Thickness/ Reapplication Rate)(in/min)[a]	Satisfactory Foam Types (Minimum Thickness/ Reapplication Rate)(in/min)[a]	Ineffective/Dangerous Foam Types (Reason)
INORGANICS (con't)	Ammonia	Surfactant H (30/10)	AFFF (8/5) Alcohol (8/5) Surfactant (8/5) Fluoroprotein (8/5) Protein (8/5)	None
INORGANIC	Bromine and chlorine	Hazmat NF #2 (ND) Surfactant H (ND) MSA Type V (ND)	None	Other foams are ineffective for use on chlorine, causing accelerated boil-off of heavier-than-air chlorine gas.

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[a] Reapplication times are generally based on the amount of time before a 1-percent vapor concentration by volume is established above the spill surface.

[b] No data are available on foam thickness or reapplication rate.

[c] H - high-expansion surfactant foam; L = low-expansion or medium-expansion surfactant foam.

[d] Hazmat NF #1, Hazmat NF #2, and MSA Type V are specified by name because they were designed for controlling hazardous vapors. This is not an endorsement.

TABLE 9-2. PERFORMANCE SUMMARY OF THREE UNIVERSAL AND SPECIALTY FOAMS

Foam: National Universal Foam

General Applicability

Multi-purpose foam for extinguishing hydrocarbon, alcohol, and polar solvent fires; also for vapor control for hydrocarbons, alcohols, polar solvents, and chemically neutral materials.

Chemicals for Which this Foam is Ineffective:

Chlorosulfonic Acid
Fluorosulfonic Acid
Phosgene
Phosphorus Oxychloride
Phosphorus Trichloride
Sulfuryl Chloride

Foam: Hazmat NF® Foam Number 1

General Applicability

Foam for vapor control for alkaline materials spills.

Chemicals for Which this Foam is Ineffective:

(see Table 9-1)

Foam: Hazmat NF® Foam Number 2

General Applicability

Foam for vapor control for acid material spills.

Chemicals for Which this Foam is Ineffective:

(see Table 9-1)

Foam: MSA VEEFOAM™

General Applicability

Multi-purpose foam for extinguishing fires and control of vapors; provides effective vapor control for water-immiscible organic liquids and acid and alkaline inorganic materials; can be used in low- and high-expansion foam generating equipment.

Chemicals for Which this Foam is Ineffective:

Polar compounds (with dielectric constant greater than 15)
Some organic acids
Some inorganic acis
Uncontained spills of liquified gases

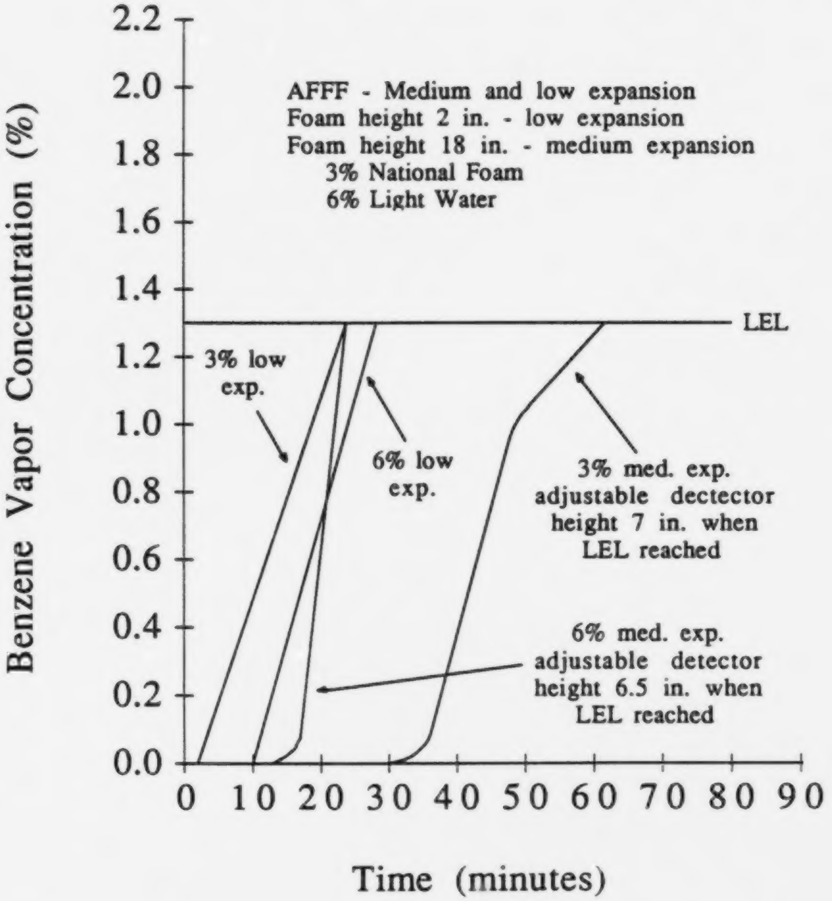

Figure 9-1. Benzene vapor concentration versus time.

Source: Adapted from Reference 3.

9.5 RELIABILITY

Information concerning the reliability of foam systems for use in mitigating the release of flammable and/or toxic vapors from chemical spills does not appear in the literature; however, in general, the reliability of any system depends on the reliability of the system's components, human factors, interactions, and controls, as discussed in the section on spray systems.

The reliability of foam systems in emergency situations, either for fire or spill control, depends on regular inspection, maintenance, and testing of foam concentrates and application equipment.

To evaluate the reliability of foam concentrates on hand for emergency responses the following should be considered (10):

- Storage in accordance with the manufacturer's instructions, including shelf life;
- Protection from exposure to extremes of heat and cold;
- Adequate precautions to avoid contamination with other materials; and
- Inspection of concentrate for formation of any precipitates that may affect the foam's performance or render the foam concentrate useless in an emergency.

For foam-generating and applicating equipment, adequate procedures should be included for periodic inspection, maintenance, and testing of various components of the system without actually producing the foam on a full-scale emergency basis. Valving, piping, and any electrical controls can be checked for proper operation and to ensure that corrosion has not rendered the system inoperative. If special test equipment and qualified personnel are available, some important equipment performance characteristics can be checked against the results of tests conducted when the equipment was first installed or accepted. These include (10):

- The foam equipment discharge pattern;
- The percent concentration of the foam concentrate in the foam solution;
- The expansion ratio of the foam;
- The quarter drainage rate of the foam; and
- The film-forming characteristic of the concentrate.

9.6 SECONDARY HAZARDS

The primary purpose of using foam for controlling vapors from hazardous chemical spills is to minimize hazards to plant personnel, emergency spill response teams, and the general public. However, if the selected foam is incompatible with the spilled material, more vapors may actually be released than controlled. For example, certain types of foams may lose their liquid quickly and form openings in the foam layer, causing rapid generation of flammable vapors from some chemicals (i.e., liquified natural gas spills). Selection of a slow-draining foam that maintains an effective blanket over the spill but that allows the gas to become buoyant enough for safe dispersal over a period of time can eliminate this major secondary hazard. Also, if the wrong foam is used to respond to a spill of an inorganic water-reactive chemical, more vapor could be released than if no foam had been used in the first place.

Foams that cause increased vaporization should not be used in totally enclosed areas by personnel without adequate safety precautions, including self-contained breathing apparatus and protective clothing. Alternatively, a foam should be selected that is specifically formulated to reduce this secondary vaporization hazard.

Protective clothing should be worn where mobile equipment is used. Appropriate breathing apparatus should also be used by response personnel. Personnel should be properly trained in the use of all safety equipment to minimize exposure to spilled liquids and hazardous vapors.

9.7 COSTS

Costs for foam and foam application systems vary widely and depend on the type of foam selected and the type and complexity of equipment used. Approximate costs, for illustrative purposes only, for various foams to industrial customers are presented in Table 9-3 (12).

Note that the prices in Table 9-3 are approximations; the actual prices may differ, depending on the volume of foam concentrate purchased by a customer and on the particular distribution system.

Costs for application equipment also vary, ranging from small manually operated portable systems to large automatically operated fixed systems and self-contained mobile foam trucks. Examples of foam application equipment costs are shown in Table 9-4 (12,13).

TABLE 9-3. APPROXIMATE COSTS FOR VARIOUS FOAMS

Type of Foam	Cost ($/Gallon)
Regular protein foam (3 percent formulation)	$8/gallon
Surfactant foam (1.5 percent formulation)	$11/gallon
Aqueous film forming foam (3 and 6 percent formulations)	$9 - $12/gallon (depending on formulation)
Alcohol type foam (3 and 6 percent formulations)	$14 - $15/gallon (depending on formulation)
Specialty foams (6 percent formulations)	$15/gallon

TABLE 9-4. EXAMPLES OF FOAM APPLICATION EQUIPMENT COSTS

Equipment	Cost 1987 ($)
Smallest manually operated portable systems	$ 125
Larger manually operated portable system with nozzle and eductor	$ 600
Modification of city fire department pumper for 1 to 2 foam discharge lines	$1,200 to $1,500
Skid-mounted foam system for semi-fixed or permanent installation	$15,000 to $100,000, depending on whether full automatic control is required
Trailer-mounted foam system	$6,000 to $30,000, depending on size
Self-contained mobile foam trucks with storage for foam concentrate and water	$120,000 to $400,000, depending on additional safety and spill control equipment needed
Fully automatic high-expansion foam generators for total flooding	$8,000 to $25,000
Small portable high-expansion foam generators	$1,000 to $1,500

9.8 REFERENCES

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APPENDIX A

TABLE A-1. METRIC (SI) CONVERSION FACTORS

Quantity	To Convert From	To	Multiply By
Length:	in	cm	2.54
	ft	m	0.3048
Area:	in^2	cm^2	6.4516
	ft^2	m^2	0.0929
Volume:	in^3	cm^3	16.39
	ft^3	m^3	0.0283
	gal	m^3	0.0038
Mass (weight):	lb	kg	0.4536
	short ton (ton)	Mg	0.9072
	short ton (ton)	metric ton (t)	0.9072
Pressure:	atm	kPa	101.3
	mm Hg	kPa	0.133
	psia	kPa	6.895
	psig	kPa*	(psig+14.696)x(6.895)
Temperature:	°F	°C*	(5/9)x(°F-32)
	°C	K*	°C+273.15
Caloric Value; Enthalpy:	Btu/lb	kJ/kg	2.326
	Btu/lbmol	kJ/kgmol	2.326
	kcal/gmol	kJ/kgmol	4.184
Specific-Heat Capacity:	Btu/lb-°F	kJ/kg-°C	4.1868
Density:	lb/ft^3	kg/m^3	16.02
	lb/gal	kg/m^3	119.8
Concentration:	oz/gal	kg/m^3	
	quarts/gal	cm^3/m^3	25,000
Flowrate:	gal/min	m^3/min	0.0038
	gal/day	m^3/day	0.0038
	ft^3/min	m^3/min	0.0283
Velocity:	ft/min	m/min	0.3048
	ft/sec	m/sec	0.3048
Viscosity:	centipoise (CP)	kg/m-s	0.001

*Calculate as indicated